

HANDBOOK OF SUSTAINABLE INDUSTRIAL WASTEWATER TREATMENT



EDITED BY HIND ABDELLAOUI



CRC Press
Taylor & Francis Group

Handbook of Sustainable Industrial Wastewater Treatment

The *Handbook of Sustainable Industrial Wastewater Treatment* is an indispensable resource for addressing the pressing challenges of wastewater management through innovative and sustainable technologies. This comprehensive guide delves into the intricacies of pollutant classification, the impacts of climate change, and a variety of effective treatment methods, making it a must-have for professionals in the field.

This handbook equips readers with the essential knowledge to maintain efficient water treatment systems while implementing sustainable practices that prioritize environmental protection. It showcases cutting-edge treatment technologies capable of removing over 99% of contaminants, all while minimizing maintenance needs, energy consumption, and chemical usage. By offering eco-friendly solutions that significantly reduce operational costs, this handbook emerges as a vital tool for enhancing wastewater management practices across industries.

In addition to traditional methods, this handbook explores innovative strategies that not only improve water quality but also promote resource conservation, ultimately supporting broader environmental sustainability goals. Tailored specifically for researchers, academicians, and professionals in hydrology, environmental science, agricultural engineering, and water resource management, this handbook also benefits postgraduate and doctoral students engaged in water-related research.



Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

Handbook of Sustainable Industrial Wastewater Treatment

Edited by
Hind Abdellaoui



CRC Press

Taylor & Francis Group

Boca Raton London New York Leiden

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

A BALKEMA BOOK

Designed cover image: Shutterstock.com

First published 2026

by CRC Press/Balkema

4 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN

and by CRC Press/Balkema

2385 NW Executive Center Drive, Suite 320, Boca Raton FL 33431

CRC Press/Balkema is an imprint of the Taylor & Francis Group, an informa business

© 2026 selection and editorial matter, Hind Abdellaoui; individual chapters, the contributors

The right of Hind Abdellaoui to be identified as author of the editorial material, and of the authors for their individual chapters has been asserted in accordance with sections 77 and 78 of the Copyright, Designs and Patents Act 1988.

All rights reserved. No part of this book may be reprinted or reproduced or utilised in any form or by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying and recording, or in any information storage or retrieval system, without permission in writing from the publishers.

Although all care is taken to ensure integrity and the quality of this publication and the information herein, no responsibility is assumed by the publishers nor the author for any damage to the property or persons as a result of operation or use of this publication and/or the information contained herein.

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

ISBN: 9781032803715 (hbk)

ISBN: 9781032803968 (pbk)

ISBN: 9781003496649 (ebk)

DOI: 10.1201/9781003496649

Typeset in Times

by codeMantra

Contents

<i>Preface</i>	vii
<i>About the Editor</i>	viii
<i>Contributors</i>	ix
1 Water Quality: The Basics Understanding and Global Water Cycle	1
<i>Hariprasad Perumal, Muthukrishnan MayaKrishnan, Felix Sahayaraj Arokyasamy, Ramadoss Prem Kumar, Sudhagar Sukkasamy, and Kannan Muthu</i>	
2 Major Water Pollutants and Contaminants: Identification and Classification	22
<i>Fatima Zahra Benbrahim, El Houssain Bouichou, Mohammed Zouini, Yasmine Azzouzi, Khaoula Boumais, and Ilias Mouallif</i>	
3 Issues and Challenges in Water Crisis: Industrial and House Wastewater Treatment	33
<i>Chaimae Belayouchia</i>	
4 Wastewater Disinfection Methods and Pollutant Removal Treatment	44
<i>Merieme Ben Ali and Sanaa Namaane</i>	
5 Degradation of Organic Contaminants in Wastewater via Hydrodynamic Cavitation Technology	59
<i>Ashok Kumar Babuchellam, Thirumarai Selvi Chandraraju, MuthuKrishnan Mayakrishnan, and Hariprasad Perumal</i>	
6 Reverse Osmosis Technology for Water Treatment and Desalination	79
<i>Prem Baboo</i>	
7 Wastewater Treatment: Use of Biopolymers as a Sustainable Approach	87
<i>Ikrame Ayouch, Soumia Aboulhrouz, Ilham Jioui, Karim Dânoun, Mina Oumam, and Mohamed Zahouily</i>	
8 Application of <i>Moringa oleifera</i> Plant for Water Treatment	100
<i>Karim Dânoun, Soumia Aboulhrouz, and Mohamed Zahouily</i>	
9 Heavy Metal Removal Using Phytoremediation Approaches	112
<i>Priyadarshini Pillai, Chinappan Balaji Ayyanar, Veluswamy Rinusuba, and Gayathri</i>	
10 Biological Wastewater Treatment: Fundamentals and Recent Development in Nutrient Removal	125
<i>Priyadarshini Pillai, Chinappan Balaji Ayyanar, Veluswamy Rinusuba, and Gayathri</i>	

11 Microbial Desalination Cells: Trends and Challenges	135
<i>Prem Baboo</i>	
12 Wastewater: Environmental, Social and Health Effects	145
<i>Hind Abdellaoui and Ilias Mouallif</i>	
13 Hydrology and Water Resources: Challenges of Climate Change Impact	157
<i>MuthuKrishnan Mayakrishnan, Thirumarai Selvi Chandraraju, Sadhasivan Gokila, and Mahalingam Jeyakumar</i>	
14 Water Sustainability: Life Cycle Assessment of Advanced Technologies	182
<i>Ahmed Azzam</i>	
<i>Index</i>	193

Preface

The *Handbook of Sustainable Industrial Wastewater Treatment* is designed to serve as a comprehensive resource for researchers, practitioners, and students in the field of wastewater treatment. As global water scarcity and environmental concerns intensify, the need for sustainable solutions has never been more critical. This book explores innovative technologies and practices that not only enhance wastewater treatment efficiency but also promote environmental stewardship.

Each chapter provides insights into cutting-edge treatment methods, pollutant removal efficiencies, and real-world applications. Our aim is to equip readers with the knowledge necessary to implement sustainable practices in their respective fields.

This handbook has the aim to inspire new research, foster collaboration, and contribute to the advancement of sustainable water management.

About the Editor

Dr. Hind Abdellaoui is currently a research scientist and R&D consultant. She received her PhD in Mechanical Engineering from the National Superior School of Electricity and Mechanics, Hassan II University, Casablanca, Morocco (2015). Her work has been awarded twice: for excellence in Mechanical Engineering at ENSEM and for best thesis at the CMEEE conference in 2015. Since 2016, she has been a professor of Composite Materials, Material Sciences, Mechanics, and Structure Analysis at the Engineering School in Rabat, Morocco. In 2020, she joined the University Mohamed VI Polytech as a post-doctoral fellow in the field of Supramolecular Nanomaterials, Composite and Nanocomposite Materials, and Nanocellulose Extraction. In addition, she joined the Institute of Nanomaterials and Nanotechnology, Moroccan Foundation for Advanced Science Innovation and Research (MASCIR), Rabat, as a scientific collaborator (2014). Her contributions have appeared in over 30 publications as articles, book chapters, and contributed national and international conference papers. Her interest areas include reinforced/filled polymeric composites, lignocellulosic reinforced/filled polymeric composites, nanocomposites as well as manufacturing processes, characterization and prediction of composite behavior, treatment and surface modification of natural reinforcement, preparation of blend and foam composites, water resource management, and nanocellulose extraction.

Contributors

Soumia Aboulhrouz

MASCIR Foundation
Mohammed VI Polytechnic University
Ben Guerir, Morocco

Merieme Ben Ali

Mohammed VI Polytechnic University
Ben Guerir, Morocco

Felix Sahayaraj Arokyasamy

Department of Mechanical Engineering
Christ the King Engineering College
Coimbatore, Tamil Nadu, India

Ikrame Ayouch

MASCIR Foundation
Mohammed VI Polytechnic University
Ben Guerir, Morocco

Chinappan Balaji Ayyanar

Department of Mechanical Engineering
Coimbatore Institute of Technology
Coimbatore, Tamil Nadu, India

Ahmed Azzam

Sudan University of Science and Technology
Khartoum, Sudan

Yasmine Azzouzi

National School of Agriculture
Meknes, Morocco

Prem Baboo

Former DGM (Prod & Process)
Dangote Fertilizers Ltd.
Ibeju Lekki, Nigeria
National Fertilizers Ltd.
India
Fellow of Institution of Engineers
India

Ashok Kumar Babuchellam

Department of Mechanical Engineering
Nandha Engineering College
Erode, Tamil Nadu, India

Chaimae Belayouchia

Civil Engineering Department
Yarmouk University
Irbid, Jordan

Fatima Zahra Benbrahim

Ibn Tofaïl University
ENCG
Kenitra, Morocco
Moulay Ismail University
ENSAM
Meknes, Morocco

El Houssain Bouichou

Agronomy Regional Agricultural Research
Meknes, Morocco

Khaoula Boumais

Sidi Mohamed Ben Abdellah University
ENSA
Fez, Morocco

Thirumarai Selvi Chandraraju

Department of Electronics and Communication
Engineering
Srikrishna College of Engineering and
Technology
Coimbatore, Tamil Nadu, India

Karim Dânoun

MASCIR Foundation
Mohammed VI Polytechnic University
Ben Guerir, Morocco

Gayathri

Department of Chemistry
Coimbatore Institute of Technology
Coimbatore, Tamil Nadu, India

Sadhasivan Gokila

Department of Computer Science and Engineering
Christ the King Engineering College
Coimbatore, Tamil Nadu, India

Mahalingam Jeyakumar

Department of Mechanical Engineering
Christ the King Engineering College
Coimbatore, Tamil Nadu, India

Ilham Jioui

MASCIR Foundation
Mohammed VI Polytechnic University
Ben Guerir, Morocco

Ramadoss Prem Kumar

Department of Mechanical Engineering
Christ the King Engineering College
Coimbatore, Tamil Nadu, India

Muthukrishnan Mayakrishnan

Department of Mechanical Engineering
Christ the King Engineering College
Coimbatore, Tamil Nadu, India

Ilias Mouallif

National School of Arts and Crafts
Moulay Ismail University
ENSAM
Meknes, Morocco

Kannan Muthu

Department of Mechanical Engineering
Christ the King Engineering College
Coimbatore, Tamil Nadu, India

Sanaa Namaane

MASCIR Foundation
Rabat Design Center
Rabat, Morocco

Mina Oumam

Laboratory of Engineering and Materials LIMAT
Faculty of Sciences Ben M'Sick, Hassan II
University
Casablanca, Morocco

Hariprasad Perumal

Department of Mechanical Engineering
KIT-Kalaignarkaranidhi Institute of
Technology
Coimbatore, Tamil Nadu, India

Priyadarshini Pillai

Jyoti Nivas College Autonomous
Bangalore, India

Veluswamy Rinusuba

Department of Chemistry
Coimbatore Institute of Technology
Coimbatore, Tamil Nadu, India

Sudhagar Sukkasamy

Department of Mechanical Engineering
Christ the King Engineering College
Coimbatore, Tamil Nadu, India

Mohamed Zahouily

MASCIR Foundation
Mohammed VI Polytechnic University
Ben Guerir, Morocco
Laboratory of Materials, Catalysis & Natural
Resources Valorization, URAC 24
Faculty of Science and Technology, Hassan II
University
Casablanca, Morocco

Mohammed Zouini

Sidi Mohamed Ben Abdellah University
ENS
Fez, Morocco

Water Quality

The Basics Understanding and Global Water Cycle

1

Hariprasad Perumal, Muthukrishnan MayaKrishnan,
Felix Sahayaraj Arokyasamy, Ramadoss Prem Kumar,
Sudhagar Sukkasamy, and Kannan Muthu

1.1 INTRODUCTION

Water quality is a critical component of environmental health, human well-being, and economic development [1]. Water quality encompasses the chemical, physical, biological, and radiological attributes that determine water's appropriateness for various applications, such as consumption, farming, industrial use, and leisure activities. Globally, water quality faces considerable risks due to various human activities, such as industrial discharge, agricultural runoff, deforestation, urbanization, and climate change. Poor water quality not only affects the health of ecosystems but also poses significant risks to human populations [2]. According to the World Health Organization (WHO), 785 million people lack access to basic drinking water, and at least 2 billion use feces-contaminated water, which spreads diarrhea, cholera, dysentery, and typhoid. Physical characteristics like temperature and turbidity, chemical characteristics like pH and dissolved oxygen (DO) levels, and biological elements like pathogens and biological oxygen demand (BOD) all affect quality [3,4]. These parameters are essential for understanding the state of water bodies and for developing strategies to manage and improve water quality [5]. For instance, the pH level of water, which typically ranges from 6.5 to 8.5 in natural conditions, is crucial for aquatic life and can be influenced by industrial effluents and acid rain [6]. Organic pollution depletes DO levels, which should be above 5 mg/L for most aquatic creatures, causing hypoxic conditions that can kill fish and destroy biodiversity [7].

The hydrological cycle, or global water cycle, describes the constant circulation of water within the Earth's atmosphere, on land, and beneath the surface [8]. It is essential for preserving the accessibility and integrity of freshwater resources. The water cycle consists of various processes such as evaporation, condensation, precipitation, infiltration, runoff, and transpiration. These interconnected processes

help circulate water throughout the planet, moving it between the atmosphere, oceans, rivers, lakes, and groundwater systems [9].

Understanding the global water cycle is essential for comprehending the dynamics of water quality. For example, the process of precipitation, which returns water from the atmosphere to the Earth's surface, can have significant implications for water quality [10]. Acid rain occurs when rainwater absorbs atmospheric contaminants like sulfur dioxide and nitrogen oxides. Acid rain acidifies water and threatens aquatic habitats. Rainwater that recharges aquifers can also carry pesticides and nitrates, contaminating groundwater [11].

The global water cycle is also crucial for regulating the Earth's climate and supporting life. The total volume of water on Earth is estimated to be about 1.386 billion cubic kilometers, with about 97.5% of this water being saline and only 2.5% being freshwater. Of this freshwater, approximately 68.7% is locked in glaciers and ice caps, 30.1% exists as groundwater, and only 1.2% is surface water or other forms of freshwater [12]. This limited availability of water highlights the importance of maintaining water quality, as even small changes in water quality can significantly impact the availability of clean water for human use and ecological functions.

Water quality is not only a local issue but also a global concern, as water pollution and scarcity transcend national borders. Poor water quality causes millions of water-related ailments globally, despite the United Nations' (UN's) recognition of clean water and sanitation as a human right [13]. In developing countries, waterborne diseases account for a significant proportion of deaths, particularly among children under the age of five. United Nations International Children's Emergency Fund (UNICEF) claims that unsafe drinking water and poor sanitation kill 525,000 children annually from diarrhea [14].

In addition to human health, water is essential for economic development. Agriculture, which accounts for 70% of global freshwater withdrawals, is highly dependent on water quality. Poor water quality can reduce crop yields, affect food security, and increase production costs due to the need for water treatment and irrigation management [15]. For instance, salinity in irrigation water can lead to soil degradation, reducing agricultural productivity and leading to economic losses [16]. In the industrial sector, water quality is critical for processes such as manufacturing, cooling, and cleaning. Contaminated water can corrode equipment, reduce product quality, and increase operational costs [17].

Additionally, ecological health is linked to water quality. Rivers, lakes, and wetlands support a variety of species and maintain biodiversity. These ecosystems are threatened by pollution, eutrophication, and habitat loss [18]. Nutrient contamination from agricultural runoff can cause algae blooms, which deplete water oxygen and produce dead zones where aquatic life cannot thrive [19].

Humans have profoundly disrupted the natural water cycle, affecting water quality. Urbanization, deforestation, agriculture, and industry increase water pollution, while climate change alters precipitation patterns and water supply [20]. For instance, deforestation reduces tree transpiration, affecting local and regional precipitation patterns. This can reduce water availability and soil erosion, worsening water quality [21].

Climate change is also expected to have a profound impact on the global water cycle and water quality. Rising temperatures are likely to increase the rate of evaporation, leading to more intense and frequent droughts in some regions and heavier rainfall and flooding in others [22]. Droughts restrict river flow, concentrating pollutants, while floods overwhelm sewage systems and contaminate water supplies with germs and chemicals [23].

The global nature of water quality and the water cycle necessitates international cooperation and integrated management strategies. The UN's 2015 Sustainable Development Goals (SDGs) emphasize the need for sustainable water and sanitation management to tackle global water quality issues [24]. Achieving this goal requires coordinated efforts across sectors and borders, as well as the involvement of governments, communities, and individuals in water conservation and pollution prevention efforts [25].

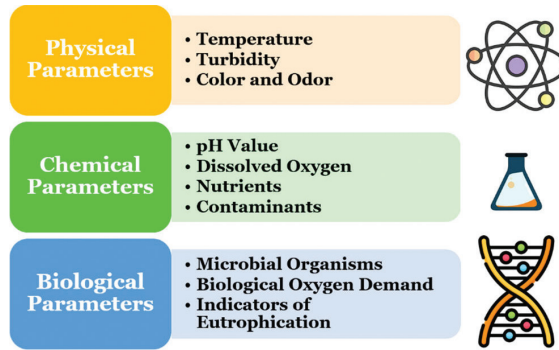


FIGURE 1.1 Water quality parameters.

1.2 WATER QUALITY PARAMETERS

1.2.1 Physical Parameters of Water Quality

Physical parameters are fundamental in assessing water quality as they influence both the aesthetic characteristics and the ecological health of water bodies [26]. Figure 1.1 illustrates the key water quality parameters, providing a comprehensive overview of factors essential for assessing and maintaining water quality standards. Key physical parameters include temperature, turbidity, color, and odor, each of which plays a crucial role in determining water's suitability for various uses.

1.2.1.1 Temperature

Water temperature is an important factor regulating chemical and biological activities in aquatic habitats. Temperature influences the solubility of gases like oxygen and the metabolic rates of aquatic organisms. For instance, the solubility of oxygen decreases as water temperature increases, which can lead to hypoxic conditions detrimental to fish and other aquatic life. Optimal temperatures for most freshwater species range between 10°C and 25°C [27]. However, industrial discharges, such as those from power plants, can elevate water temperatures, causing thermal pollution. It's found that urban streams in the United States had an average temperature increase of 0.05°C per year due to urbanization, leading to significant impacts on aquatic ecosystems [28].

1.2.1.2 Turbidity

Turbidity refers to the cloudiness or haziness of water caused by suspended particles, such as silt, clay, organic matter, and microorganisms. High turbidity can reduce light penetration, affecting photosynthesis in aquatic plants and altering the habitat of fish and invertebrates [29]. The U.S. Environmental Protection Agency (EPA) recommends a turbidity level of less than 1 nephelometric turbidity unit (NTU) for drinking water, while levels above 5 NTU can be visually noticeable and may indicate the presence of harmful microorganisms [30]. According to a study by Bilotta and Brazier, elevated turbidity levels, often caused by agricultural runoff, can lead to a 30%–90% reduction in the survival of fish eggs and larvae in freshwater systems [31].

TABLE 1.1 Physical Parameters

PARAMETER	ACCEPTABLE VALUE	REFERENCES
Turbidity	5 NTU (drinking water)	[35]
Temperature	25°C (natural waters); Ideal: 20°C–25°C	[36]
Color	5 Hazen max	[37]
Odor	<400 µS/cm (freshwater); 100–2,000 µS/cm (depending on source)	[38]

1.2.1.3 Color and odor

Color and odor are aesthetic parameters that indicate the presence of pollutants or organic matter in water. Natural water is usually colorless; however, the presence of dissolved organic materials like humic substances can impart a yellow or brown tint [32]. It's found that humic substances are prevalent in water bodies receiving significant organic runoff, such as those near agricultural lands, leading to increased color levels measured in platinum-cobalt units (PCU) [33]. Water with a color level above 15 PCU is often considered unsuitable for drinking without treatment. Odor in water, typically caused by organic decay or industrial pollution, can be a warning sign of contamination. The EPA has set secondary standards for color and odor at 15 PCU and a threshold odor number (TON) of 3, respectively, to ensure water is both safe and acceptable for consumers [34] (Table 1.1).

1.2.2 Chemical Parameters of Water Quality

Chemical parameters are crucial indicators of water quality, reflecting the presence of substances that can impact human health, aquatic life, and the usability of water. Key chemical parameters include pH, DO, nutrients, and contaminants, each influencing water quality in different ways [5].

1.2.2.1 pH value

The pH level of water measures its acidity or alkalinity on a scale from 0 to 14, with 7 being neutral. Natural waters typically have a pH range of 6.5–8.5. Extreme pH levels can harm aquatic life and affect the solubility and toxicity of chemicals in the water. For instance, a pH below 6.5 can increase the solubility of toxic metals like lead and copper, which are harmful to both humans and wildlife [39]. The rivers in Asia have shown pH levels ranging from 6.0 to 8.0, with urban rivers often leaning toward acidity due to industrial discharge [40].

1.2.2.2 Dissolved oxygen

Dissolved oxygen is a measure of the amount of oxygen available in water, crucial for the survival of aquatic organisms. DO levels typically range from 5 to 14 mg/L in healthy water bodies, with levels below 5 mg/L potentially leading to hypoxia, where aquatic life is stressed or dies off. Factors affecting DO include temperature, organic matter decomposition, and pollution [41]. The EPA sets a DO level of at least 5 mg/L for freshwater systems to support aquatic life. It's found that in the Niger Delta, DO levels often drop below 4 mg/L in polluted areas, primarily due to organic waste and oil spills, leading to significant biodiversity loss [42].

1.2.2.3 Nutrients

Nutrients like nitrogen and phosphorus are essential for aquatic life but can become pollutants when present in excess, leading to eutrophication. This process results in algal blooms, which can deplete DO and create dead zones [43]. The WHO recommends nitrate levels in drinking water not exceed 50 mg/L, while

phosphorus levels above 0.1 mg/L in surface waters can trigger eutrophication [44]. It's highlighted that agricultural runoff is a significant source of nutrient pollution, contributing to over 50% of the nitrogen and phosphorus entering water bodies in the United States [45].

1.2.2.4 Contaminants

Chemical contaminants, including heavy metals, pesticides, and industrial chemicals, pose significant risks to water quality. For example, arsenic, a toxic metal, is naturally occurring but can also be introduced through industrial activities [46]. The WHO has set the maximum allowable concentration of arsenic in drinking water at 10 µg/L [47]. Elevated levels have been reported in groundwater in South Asia, particularly in Bangladesh, where concentrations often exceed 50 µg/L, leading to widespread health issues including cancer [48]. Table 1.2 highlights the chemical parameters essential for evaluating water quality, focusing on the constituents that influence its chemical composition and overall suitability for various uses.

1.2.3 Biological Parameters of Water Quality

Biological parameters are essential in evaluating water quality, as they directly indicate the presence and abundance of living organisms, which can reflect the overall health of aquatic ecosystems. Key biological parameters include microbial organisms, BOD, and indicators of eutrophication, each of which plays a crucial role in understanding water quality dynamics [53].

1.2.3.1 Microbial organisms

The presence of microbial organisms, particularly pathogenic bacteria, viruses, and protozoa, is a critical concern for water quality, especially in drinking water sources. *Escherichia coli* (*E. coli*) is commonly used as an indicator organism to assess the presence of fecal contamination in water [54]. According to the WHO, the acceptable limit for *E. coli* in drinking water is zero colony-forming units (CFU) per 100 mL [55]. The contaminated drinking water, often due to inadequate sanitation, causes over 1.7 billion cases of diarrheal disease annually worldwide. In developing regions, microbial contamination remains a leading cause of waterborne diseases, affecting millions of people [56].

1.2.3.2 Biological oxygen demand

BOD measures the amount of oxygen needed for microorganisms to decompose organic matter in water. It is a critical parameter for assessing the degree of organic pollution in water bodies [57]. High BOD levels indicate a high amount of biodegradable material, which can lead to oxygen depletion and harm aquatic life. The U.S. EPA suggests that BOD levels in clean water should be below 3 mg/L, while values above 5 mg/L indicate pollution [58]. It's found that BOD levels in urban rivers in China often exceed 10 mg/L due to untreated sewage discharge, leading to hypoxic conditions and biodiversity loss [59].

TABLE 1.2 Chemical Parameters

PARAMETER	ACCEPTABLE VALUE	REFERENCES
pH	6.5–8.5 (drinking water) [8.0]	[49]
Dissolved oxygen (DO)	5 mg/L (healthy ecosystems); 4 mg/L (acceptable)	[50]
Nitrates (NO ₃)	10 mg/L (drinking water); 45 mg/L (surface water)	[51]
Phosphates (PO ₄ ³⁻)	<0.1 mg/L (surface water); <1 mg/L (drinking water)	[52]

1.2.3.3 Indicators of eutrophication

Eutrophication, primarily driven by excessive nutrient input, is another critical biological parameter that impacts water quality. It leads to the overgrowth of algae and subsequent depletion of oxygen in water bodies [19]. Phytoplankton biomass, measured as chlorophyll-a concentration, is a common indicator of eutrophication. The European Union’s Water Framework Directive considers chlorophyll-a concentrations above 20 µg/L as indicative of eutrophic conditions [60]. Eutrophication has significantly declined fish populations in freshwater lakes, particularly in regions with high agricultural runoff, which not only degrades water quality but also disrupts entire aquatic ecosystems [61].

1.3 GLOBAL WATER CYCLE PROCESSES AND COMPONENTS

Figure 1.2 depicts the global water cycle processes, illustrating the continuous movement of water within the Earth’s atmosphere, surface, and subsurface through key stages such as evaporation, condensation, precipitation, and runoff.

1.3.1 The Hydrological Cycle

The hydrological cycle, also known as the water cycle, is a continuous process by which water moves through the Earth’s atmosphere, land, and oceans. This cycle is essential for the distribution and availability of freshwater resources, influencing both water quality and quantity worldwide [62].

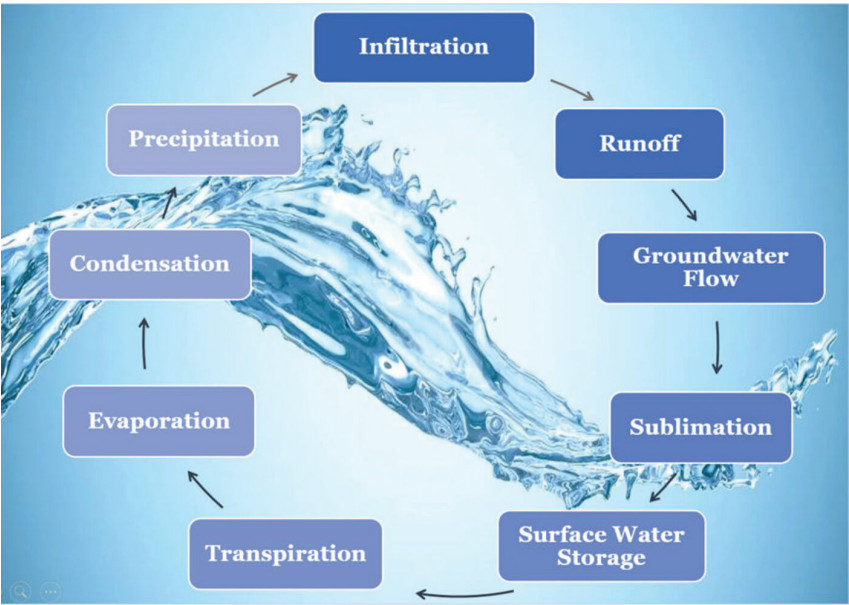


FIGURE 1.2 Global water cycle processes.

1.3.1.1 Evaporation and transpiration

The cycle begins with the evaporation of water from the Earth's surface, primarily from oceans, which cover about 71% of the planet. Approximately 90% of atmospheric moisture originates from oceanic evaporation, while the remaining 10% comes from transpiration by plants, a process known as evapotranspiration [63]. According to the U.S. Geological Survey (USGS), about 505,000 cubic kilometers of water evaporate annually, with a significant portion returning to the Earth as precipitation [12].

1.3.1.2 Condensation and precipitation

As water vapor rises, it cools and condenses into clouds. The amount of water vapor in the atmosphere at any given time is about 12,900 cubic kilometers. Precipitation occurs when these clouds release water, returning it to the Earth's surface as rain, snow, sleet, or hail. Global precipitation averages about 990 mm per year, though this varies significantly by region. For example, the Amazon rainforest receives up to 2,300 mm annually, while deserts like the Sahara may receive less than 25 mm [64].

1.3.1.3 Infiltration and percolation

Once precipitation reaches the ground, it either infiltrates the soil, replenishing groundwater reserves, or becomes surface runoff. Infiltration rates depend on soil type, land cover, and moisture levels. Globally, groundwater accounts for about 30.1% of the Earth's freshwater. The total volume of groundwater is approximately 22.6 million km³, but only a fraction is renewable and accessible for human use [65].

1.3.1.4 Runoff and collection

Surface runoff occurs when the ground is saturated or impermeable, leading water to flow over land into rivers, lakes, and eventually oceans. This process is vital for the redistribution of water and nutrients and also transport pollutants, affecting water quality [66]. Climate change will increase extreme runoff events, causing more frequent and severe flooding and soil erosion, according to the Intergovernmental Panel on Climate Change (IPCC) [67].

1.3.2 Global Impact of the Hydrological Cycle

The hydrological (or water) cycle is a fundamental process that circulates water throughout the Earth's atmosphere, surface, and subsurface. This continuous movement of water has far-reaching impacts on global ecosystems, economies, and societies [9]. Changes in the hydrological cycle, particularly due to human activities and climate change, are reshaping water availability and causing widespread environmental challenges. Below are key impacts and data associated with the global water cycle [68]. Table 1.3 outlines the global impact of the hydrological cycle, emphasizing its role in regulating climate, supporting ecosystems, and influencing water availability across different regions.

The hydrological cycle is essential for maintaining the Earth's water balance, supporting ecosystems, and sustaining human life. However, human activities such as deforestation, urbanization, and climate change are altering the natural flow of the cycle. For instance, urban areas with impermeable surfaces increase runoff and reduce groundwater recharge, leading to water scarcity and quality issues [62]. Additionally, climate change is predicted to intensify the hydrological cycle, with more extreme weather patterns, potentially exacerbating water-related challenges [79].

Human activities have profoundly altered the natural water cycle, disrupting the delicate balance of water distribution and quality worldwide. These impacts, driven by urbanization, deforestation, agriculture, and climate change, have far-reaching consequences for both the availability and quality of water resources [80].

TABLE 1.3 Global Impact of the Hydrological Cycle

<i>CATEGORY</i>	<i>GLOBAL IMPACT</i>	<i>RECENT FINDS</i>	<i>REFERENCES</i>
Total global water distribution	97.5% of Earth's water is saline, and 2.5% is freshwater	68.7% of freshwater is in glaciers, 30.1% is groundwater	[69]
Global evaporation	Total volume of water evaporating from Earth's surface annually	~500,000 km ³ of water evaporates per year	[70]
Annual precipitation	Average amount of water returning to Earth's surface as precipitation	~110,000 km ³ of water falls as precipitation annually	[70]
Runoff and surface water flow	Water moving across the surface into rivers and oceans	~40,000 km ³ of water contributes to global runoff	[70]
Groundwater use	Volume of groundwater used globally for irrigation, drinking, etc.	~1,000 km ³ per year extracted for human use	[71]
Water cycle disruption due to climate change	Changing precipitation patterns and evaporation rates	~20% increase in evaporation rates in certain regions due to warming	[72]
Ocean circulation	Impact on sea level and ocean salinity due to water cycle changes	Sea level rise: 3.4 mm/year on average (global)	[73]
Agricultural water use	Water consumed by global agriculture, a key component of the water cycle	70% of freshwater is used for agriculture globally	[74]
Water stress and scarcity	Areas experiencing severe water shortages due to water cycle imbalance	2.4 billion people live in water-stressed regions	[75]
Glacial melt and water supply	Glacial melt contributes to river systems and sea levels	Glaciers provide water to 1.9 billion people but are melting rapidly	[76]
Flooding and drought events	Frequency and severity of hydrological events	Increase in floods by 24%, droughts by 32% in the last decade	[77]
Sea level rise	Contribution from melting ice and thermal expansion	The global sea level is rising by 3.7 mm per year	[78]

1.3.2.1 Urbanization

Urbanization significantly alters the water cycle by increasing surface runoff and reducing groundwater recharge. As cities expand, permeable surfaces like forests and fields are replaced with impermeable surfaces such as roads and buildings. This change reduces the amount of water that infiltrates into the ground, leading to lower groundwater levels [81]. The urbanization in the Pearl River Delta of China reduced groundwater recharge by 40% between 1980 and 2005. Additionally, increased runoff can overwhelm stormwater systems, leading to frequent flooding and water pollution as contaminants are washed into rivers and lakes [82].

1.3.2.2 Deforestation

Deforestation disrupts the hydrological cycle by reducing evapotranspiration and increasing runoff and soil erosion. Trees play a critical role in the water cycle by absorbing water through their roots and releasing it into the atmosphere through transpiration. The elimination of forests decreases this process, leading to reduced local precipitation and changes in weather patterns [83]. Deforestation in the Amazon basin could reduce regional rainfall by up to 20%, affecting both local and global water cycles. Furthermore, deforestation increases surface runoff, which can cause soil erosion and sedimentation in rivers, degrading water quality and aquatic habitats [84].

1.3.2.3 Agriculture

Agricultural practices also significantly impact the water cycle, primarily through irrigation and the use of fertilizers. Irrigation alters the natural flow of water, often leading to the depletion of surface water and groundwater resources [85]. The Food and Agriculture Organization (FAO) reports that agriculture accounts for 70% of global freshwater withdrawals, with some regions, like the Middle East, using over 90% of available freshwater for agriculture. Overextraction of groundwater for irrigation has led to declining water tables, particularly in regions like India and the United States. For example, the Ogallala Aquifer in the U.S. has seen water levels drop by more than 30m in some areas due to agricultural pumping [86].

1.3.2.4 Climate change

One of the biggest human-induced water cycle changes is climate change. Global warming accelerates evaporation, alters precipitation patterns, and increases the frequency and intensity of extreme weather events like floods and droughts [87, 88].

1.3.2.5 Global implications

The cumulative impact of these human activities is a disrupted water cycle, with significant implications for water availability, quality, and ecosystem health [62]. Managing these impacts requires a comprehensive approach that includes sustainable urban planning, reforestation, efficient agricultural practices, and global efforts to mitigate climate change. Without such measures, the pressures on the water cycle will continue to grow, leading to more severe water-related challenges in the future [89].

1.4 INTERCONNECTION BETWEEN WATER QUALITY AND THE GLOBAL WATER CYCLE

The water cycle, a fundamental natural process, is pivotal in determining water quality. Through the continuous movement of water between the atmosphere, land, and oceans, the water cycle influences the chemical, physical, and biological characteristics of water bodies. This section reviews recent findings on how various stages of the water cycle—precipitation, runoff, infiltration, and evaporation—impact water quality, emphasizing the most recent research and numerical data [90].

1.4.1 Precipitation and Water Quality

Precipitation, the primary mechanism for delivering water from the atmosphere to the Earth's surface, directly influences water quality by introducing various dissolved substances and particulates. Recent studies have highlighted the role of atmospheric pollution in altering the composition of precipitation [91]. In urban areas, rainwater contains high concentrations of nitrates and sulfates, which are byproducts of industrial emissions. In Beijing, China, the average nitrate concentration in precipitation was found to be 1.4 mg/L, significantly higher than in rural areas. This “acid rain” phenomenon lowers the pH of surface waters, leading to increased metal solubility and potential toxicity to aquatic life [92].

Furthermore, precipitation acts as a vector for transporting airborne pollutants, such as heavy metals and persistent organic pollutants (POPs), into aquatic ecosystems. For instance, a study conducted in India found that annual monsoon rains deposited up to 3.5 µg/L of lead into freshwater bodies, significantly impacting water quality and posing risks to human health [93].

1.4.2 Surface Runoff and Pollutant Transport

Surface runoff is a critical stage in the water cycle where water moves across the land's surface, often carrying pollutants from agricultural, urban, and industrial sources. Runoff is a significant vector for nonpoint source pollution, degrading water quality in rivers, lakes, and coastal areas. According to the U.S. EPA, runoff from agricultural lands is the leading source of water pollution in the United States, contributing to 70% of the nation's water quality problems [94].

The impact of agricultural runoff on water quality in the Mississippi River Basin, where nutrient loading, particularly nitrogen and phosphorus, has led to hypoxic zones in the Gulf of Mexico [95]. The study reported average nitrogen concentrations of 7.1 mg/L in surface waters, significantly above the EPA's recommended limit of 10 mg/L for drinking water. These elevated nutrient levels contribute to eutrophication, leading to harmful algal blooms and oxygen depletion, which severely affect aquatic life [96].

1.4.3 Infiltration and Groundwater Quality

Infiltration, the process by which water permeates the soil and recharges groundwater, is another critical phase where the water cycle affects water quality. Groundwater quality is influenced by the soil's ability to filter out pollutants as water percolates through it. However, recent research has shown that in areas with heavy agricultural or industrial activities, contaminants can bypass natural filtration processes and enter groundwater supplies [97]. It is reported nitrate concentrations in groundwater as high as 45 mg/L, primarily due to the infiltration of agricultural fertilizers. This level exceeds the WHO's safe drinking water limit of 50 mg/L, highlighting the risk of groundwater contamination in agricultural regions. The study also found elevated levels of pesticides in groundwater, with concentrations of organochlorine pesticides reaching up to 0.2 µg/L, posing a significant health risk to local populations [98].

1.4.4 Evaporation and Concentration of Pollutants

Evaporation, which returns water from surface bodies back into the atmosphere, can concentrate pollutants in the remaining water. Evaporation rates diminish water volumes and increase salts, heavy metals, and other toxins in dry and semiarid locations, making this process important [69]. Evaporation rates of over 60% led to salinity levels in some water bodies reaching 5,000 mg/L, far exceeding the WHO guideline of 1,000 mg/L for drinking water. This concentration of pollutants due to evaporation also exacerbates issues such as the salinization of soils and the degradation of water quality in reservoirs and lakes, impacting both agricultural productivity and the availability of safe drinking water [99].

1.5 HOW WATER QUALITY INFLUENCES THE WATER CYCLE?

Water quality significantly influences the various components and processes of the water cycle, creating feedback loops that can alter the cycle's dynamics. Poor water quality, often driven by anthropogenic activities, affects evaporation rates, cloud formation, precipitation patterns, and groundwater recharge. Recent research and review papers provide insights into how contaminants and changes in water quality affect the water cycle on a global scale [100].

1.5.1 Evaporation and Pollutant Concentration

Water quality directly impacts the evaporation process, particularly through the concentration of pollutants. As water evaporates, dissolved substances, such as salts, heavy metals, and organic compounds, are left behind, leading to an increase in their concentration in the remaining water body. The Tigris-Euphrates basin highlighted that high evaporation rates in arid regions led to a significant increase in salinity levels, reaching up to 5,000 mg/L. This salt concentration decreases water quality and alters its physical and chemical properties, such as vapor pressure and evaporation rate, affecting the water cycle [101].

Moreover, pollutants in evaporating water can influence the formation of aerosols, which play a crucial role in cloud formation and precipitation. Pollutants, particularly, fine particulate matter from industrial sources, act as cloud condensation nuclei (CCN), altering cloud microphysics [102]. Pollutants in clouds can change cloud albedo, precipitation efficiency, and even the frequency and intensity of rainfall. This feedback mechanism demonstrates how degraded water quality can indirectly influence the hydrological cycle by affecting the formation and behavior of clouds [103].

1.5.2 Precipitation and Acid Rain

The quality of water in the atmosphere, influenced by airborne pollutants, directly affects precipitation. Acid rain, which forms when sulfur dioxide (SO_2) and nitrogen oxides (NO_x) released from industrial activities combine with atmospheric moisture, is a prime example of this interaction [104]. Acid rain not only degrades surface water quality but also influences soil and vegetation, which in turn affects the infiltration and runoff phases of the water cycle. China reported that acid rain, with a pH as low as 4.3, is common in heavily industrialized regions [105]. This acidic precipitation alters the natural chemical balance of soil and water bodies, reducing their buffering capacity and leading to the leaching of harmful metals like aluminum into groundwater. These changes in water chemistry can affect the overall flow and storage of water within the hydrological cycle, potentially altering local and regional water availability [106].

1.5.3 Runoff, Eutrophication, and the Hydrological Cycle

Eutrophication, caused by nutrient-rich runoff from agricultural lands, is another significant way water quality influences the water cycle. Excess nutrients, particularly nitrogen and phosphorus, lead to algal blooms in water bodies. These blooms not only degrade water quality by depleting oxygen levels but also affect the hydrological cycle by altering evaporation and precipitation patterns [107].

The Mississippi River Basin found that nutrient runoff significantly increased algal biomass in downstream water bodies. The resulting eutrophication led to changes in water temperature and chemistry, which in turn influenced local evaporation rates. Increased algal growth can create thermal stratification in lakes, where surface waters warm faster and evaporate more readily, while deeper waters become oxygen-deprived. This altered thermal profile affects the entire local hydrological cycle, potentially leading to changes in regional weather patterns and water availability [108].

1.5.4 Groundwater Contamination and Recharge

Contaminated water also impacts groundwater recharge, a critical water cycle component. Pollutants from surface water can percolate into groundwater, reducing the quality and quantity of recharge. In areas with heavy pesticide or fertilizer use, contaminants can leach into aquifers, affecting the overall hydrological balance [109]. Nitrate contamination from agricultural runoff led to groundwater nitrate levels of up to

45 mg/L. This contamination not only poses health risks but also alters the natural recharge process, as contaminated groundwater can affect the soil’s ability to retain and transmit water. Over time, this reduces groundwater storage and availability, disrupting the natural cycle of groundwater discharge and surface water flow [110].

1.5.5 Feedback Mechanisms and Global Implications

The interactions between water quality and the water cycle create complex feedback mechanisms that can amplify environmental changes. As poor water quality leads to altered evaporation or precipitation patterns, these changes can further degrade water quality, creating a vicious cycle. Climate change exacerbates these effects by intensifying the impacts of pollution on the water cycle [111]. The IPCC predicts that rising global temperatures will exacerbate the hydrological cycle, causing more intense weather and water quality issues. Understanding these processes is essential for establishing water quality mitigation methods for the water cycle. Improving wastewater treatment, lowering pollutant emissions, and controlling land use practices maintain water quality and promote water cycle sustainability in a changing climate [112].

1.6 GLOBAL CHALLENGES IN WATER QUALITY AND WATER CYCLE

Figure 1.3 illustrates the global challenges associated with water quality and the water cycle, highlighting issues such as pollution, scarcity, climate change impacts, and their interconnected effects on water resources.

The interplay between water quality and the water cycle presents many global challenges, driven by natural processes and exacerbated by human activities. Population development, industrialization, and climate change are increasing water resource strains, making water quality and water cycle management difficult. This chapter addresses global challenges using contemporary research, numerical data, and comparative analysis [113].



FIGURE 1.3 Global challenges in water quality and water cycle.

1.6.1 Water Scarcity and Demand

Water scarcity is a pressing global issue, impacting over 2 billion people worldwide. According to the UN Water Report, nearly 1.2 billion people live in areas of physical water scarcity, where water availability is less than 1,000 m³ per person per year. Additionally, about 500 million people face economic water scarcity, where water is available but inaccessible due to financial or infrastructural constraints [114]. The growing demand for water due to population growth and economic development is straining available resources. The World Resources Institute (WRI) projects that by 2040, water demand will exceed supply in 33 countries, primarily in regions like the Middle East and North Africa, where water scarcity is already acute [115].

1.6.2 Pollution and Contamination

Water pollution poses a significant threat to water quality and human health. Industrial discharges, agricultural runoff, and improper waste disposal introduce various contaminants into water bodies. Recent data reveal alarming levels of pollution [116].

1.6.2.1 Nutrients

Excessive nutrients, particularly nitrogen and phosphorus from agricultural runoff, lead to eutrophication in water bodies. The European Environment Agency (EEA) reports that nutrient pollution affects over 50% of European water bodies, causing algal blooms and hypoxic zones [117]. In the Gulf of Mexico, the Dead Zone—an area with severely depleted oxygen levels—has expanded to over 22,000 km² due to nutrient runoff from the Mississippi River Basin [118].

1.6.2.2 Heavy metals

Industrial activities contribute to heavy metal contamination, with arsenic, lead, and mercury being prominent concerns. The WHO sets the maximum allowable concentration of arsenic in drinking water at 0.01 mg/L. However, studies reveal concentrations exceeding this limit in several regions. For example, groundwater in Bangladesh has arsenic levels up to 0.5 mg/L, posing severe health risks [47].

1.6.2.3 Microbial contaminants

Pathogenic microorganisms, including bacteria, viruses, and protozoa, contaminate water sources, leading to waterborne diseases. The WHO estimates that 1.8 million deaths annually are attributed to diarrheal diseases caused by contaminated water. The presence of *E. coli* is used as an indicator of fecal contamination, with acceptable levels set at zero CFU per 100 mL of drinking water. Yet, in many developing countries, *E. coli* contamination is widespread, reflecting inadequate sanitation and water treatment [119].

1.6.3 Climate Change Impacts

Climate change significantly affects the water cycle and water quality. Increasing temperatures, changes in precipitation patterns, and more frequent extreme weather events impact both the availability and quality of water resources. The climate change is altering global precipitation patterns, leading to increased frequency of both droughts and heavy rainfall events. The IPCC predicts that worldwide precipitation will rise by 2%–3%

per degree Celsius of warming by 2100, with significant regional variability. The Sahel in Africa has suffered extended droughts, whereas Southeast Asia has witnessed increased flooding, hurting water supply and quality.

Rising temperatures increase water temperatures in lakes, rivers, and oceans, affecting aquatic ecosystems. Warmer water holds less dissolved oxygen, leading to hypoxic conditions that can harm marine life. The National Oceanic and Atmospheric Administration (NOAA) reports that surface water temperatures in the Great Lakes have increased by 1.2°C over the past century, impacting fish populations and water quality [120]. Melting glaciers and ice caps contribute to rising sea levels, which can lead to saltwater intrusion into freshwater aquifers. In coastal regions, saltwater intrusion compromises groundwater quality, affecting freshwater availability for drinking and agriculture. The IPCC estimates that global sea levels have risen by about 0.2 m since 1901, with projections of an additional rise of 0.3–1.1 m by 2100 [121].

1.6.4 Urbanization and Infrastructure

Urbanization intensifies pressures on water resources through increased water demand, pollution, and altered hydrological patterns. Urban areas with impermeable surfaces, such as roads and buildings, increase surface runoff and reduce groundwater recharge. According to the UN-Habitat [2020], over 55% of the global population now lives in urban areas, and this number is expected to rise to 68% by 2050 [122]. The impact of urbanization on water quality includes urban runoff that often carries pollutants such as oils, heavy metals, and debris into water bodies. The EPA reports that urban runoff is a leading cause of water pollution in the United States, affecting over 70% of assessed water bodies. This runoff contributes to higher concentrations of contaminants and increased sedimentation in rivers and lakes [123]. Many urban areas face challenges with aging water infrastructure, leading to leaks, contamination, and inefficient water management. The American Society of Civil Engineers (ASCE) estimates that the U.S. needs to invest \$271 billion in water infrastructure over the next 20 years to address these issues and improve water quality [124].

1.6.5 Water Management and Policy

Effective water management and policy are crucial in addressing these global challenges. Integrated water resources management (IWRM) approaches and policies designed to reduce pollution, manage demand, and adapt to climate change are vital. The UN's Sustainable Development Goal 6 emphasizes the importance of clean water and sanitation, highlighting the necessity of implementing policies that are vital for maintaining sustainable water resources [125].

1.7 FUTURE DIRECTIONS AND SOLUTIONS

Addressing the complex challenges of water quality and the water cycle requires innovative solutions and strategic approaches. Recent studies and real-time applications highlight several promising directions for improving water management, mitigating pollution, and adapting to climate change impacts. This section explores these future directions and solutions based on recent research and practical applications.

Emerging water treatment technologies are crucial for improving water quality and managing contaminants. Recent studies highlight the importance of developing and implementing advanced treatment methods to tackle pollutants that conventional systems find challenging to eliminate. Researchers are exploring the use of nanomaterials for water purification. Nanocomposites have proven highly effective in removing heavy metals and organic contaminants from water, owing to their large surface area,

customizable surface chemistry, and superior adsorption and catalytic capabilities. The application of nanoscale materials, such as titanium dioxide and graphene oxide, has demonstrated potential in breaking down pollutants and enhancing water quality. Real-time applications include the integration of nanomaterials in water filtration systems for both industrial and residential use [126].

Advances in membrane filtration technologies, such as reverse osmosis and nanofiltration, are improving the elimination of contaminants from water. The creation of high-performance membranes with improved filtration efficiency and increased resistance to fouling are employed in desalination plants and wastewater treatment facilities to provide cleaner and safer water [127].

IWRM approaches are gaining traction as a means to address water quality and quantity challenges holistically. Recent research emphasizes the importance of managing water resources collectively considering all aspects of the water cycle. The benefits of catchment-based water management involve coordinating efforts across entire river basins to address pollution and water scarcity. Real-time applications include the implementation of watershed management plans that integrate land use planning, pollution control, and conservation efforts. For example, the Water Framework Directive in Europe promotes catchment management to improve water quality across river basins [128].

The application of digital technologies and data analytics is transforming water management practices. Smart water systems, which incorporate sensors, real-time monitoring, and data analytics, can efficiently manage water resources. The deployment of smart sensors for real-time water quality monitoring and leak detection in urban water systems helps optimize water distribution, detect contamination events, and reduce water loss [129].

Adapting to climate change is essential for maintaining water quality and managing the water cycle. Recent studies focus on strategies to mitigate the impacts of climate change on water resources. Green infrastructure, such as rain gardens, green roofs, and permeable pavements, is implemented to manage stormwater and reduce runoff. The green infrastructure in urban areas allow effectively to improve the water quality and reduce the flood risks. Real-time applications include the integration of green infrastructure in city planning to manage stormwater and enhance groundwater recharge [130].

Developing climate-resilient water systems involves designing infrastructure and management practices that can withstand extreme weather events. Climate-resilient water supply systems in coastal areas are prone to sea level rise and saltwater intrusion. Real-time applications encompass the construction of seawalls, enhancement of drainage systems, and the utilization of alternative water sources to ensure a reliable supply of freshwater [131].

Increasing public awareness and developing effective policies are critical for addressing water quality and cycle challenges. Engaging communities in water conservation and pollution prevention is essential for improving water quality. Successful community-based water management programs involve local stakeholders to monitor and protect water resources. Real-time applications include public education campaigns and citizen science projects that encourage community participation in water quality monitoring and conservation efforts [132].

Strong policies and regulations are necessary to address water quality issues and manage the water cycle effectively. Recent research highlights the necessity for updated regulations to address emerging contaminants and manage water resources sustainably. For example, the U.S. EPA has introduced new regulations for managing PFAS (per- and polyfluoroalkyl substances) in drinking water, reflecting the need for updated policies to address evolving water quality challenges [133].

Sustainable agricultural practices are essential for reducing nutrient runoff and improving water quality. Precision agriculture techniques, such as targeted fertilization and optimized irrigation, are employed to reduce nutrient runoff and minimize environmental impact. The effective precision in agriculture allows to reduce nitrogen leaching and improve the crop yields. Real-time applications involve the utilization of GPS and remote sensing technologies to enhance the efficiency of fertilizers and water distribution [134]. Implementing cover crops and conservation tillage practices helps reduce soil erosion and nutrient runoff. The practices improve soil health and water quality by enhancing nutrient retention and reducing erosion. Real-time applications involve the adoption of conservation practices in farming to protect water resources and improve sustainability [135].

1.8 CONCLUSION

This chapter provides the intricate relationship between water quality and the water cycle, which underscores the complexity of managing and safeguarding our vital water resources. This chapter has explored the fundamental aspects of water quality, including physical, chemical, and biological parameters, and examined how these parameters are influenced by and, in turn, influence the water cycle. The challenges outlined—ranging from pollution and climate change to urbanization and water scarcity—highlight the pressing need for comprehensive and adaptive management strategies. Advanced treatment technologies, such as nanotechnology and membrane filtration, offer promising solutions for enhancing water quality. IWRM and smart water systems provide frameworks for more holistic and data-driven approaches to managing water resources. Strategies for climate adaptation, such as green infrastructure and climate-resilient systems, are essential for alleviating the effects of climate change on water resources.

Moreover, sustainable agricultural practices and robust policy development are crucial for addressing the root causes of water quality issues and ensuring the long-term sustainability of water resources. Public awareness and community engagement further play a crucial role in fostering collective action and the stewardship of water resources. As we move forward, it is imperative to continue advancing scientific research, embracing innovative technologies, and implementing effective policies to address the dynamic challenges facing water quality and the water cycle. By integrating these efforts, we can enhance our ability to manage water resources sustainably and ensure a resilient and secure water future for generations to come.

REFERENCES

1. Alcamo J. Water quality and its interlinkages with the sustainable development goals. *Curr Opin Environ Sustain*. 2019;36:126–140.
2. Bashir I, Lone FA, Bhat RA, Mir SA, Dar ZA, Dar SA. Concerns and threats of contamination on aquatic ecosystems. In: *Bioremediation and Biotechnology: Sustainable Approaches to Pollution Degradation*. 2020; pp. 1–26. doi:10.1007/978-3-030-35691-0_1
3. Aneesh MR. Quality of drinking water and sanitation in India. 2021;15(1):138–152. doi:10.1177/09737030211003658
4. Abubakar IR. Factors influencing household access to drinking water in Nigeria. *Util Policy*. 2019;58:40–51.
5. Uddin MG, Nash S, Olbert AI. A review of water quality index models and their use for assessing surface water quality. *Ecol Indic*. 2021;122:107218.(Duplicate)
6. Saalidong BM, Aram SA, Otu S, Lartey PO. Examining the dynamics of the relationship between water pH and other water quality parameters in ground and surface water systems. *PLoS ONE*. 2022;17(1):e0262117. doi:10.1371/journal.pone.0262117
7. S. O'Boyle. Oxygen depletion in coastal waters and the open ocean: hypoxia and anoxia cases and consequences for biogeochemical cycling and marine life. In: *Coastal and Deep Ocean Pollution*. 2020; pp. 41–67. doi:10.1201/b22488
8. Kraft B, Jung M, Körner M, Koirala S, Reichstein M. Towards hybrid modeling of the global hydrological cycle. *Hydrol Earth Syst Sci*. 2022;26(6):1579–1614.
9. Chakraborty SK. Water: its properties, distribution, and significance. *River Ecol*. 1:2021. doi:10.1007/978-3-030-53897-2_2
10. Ryberg KR, Chanat JG. Climate extremes as drivers of surface-water-quality trends in the United States. *Sci Total Environ*. 2022;809:152165.
11. Ali SR. Impacts of acid rain on environment. *Inter Multidiscip Res J*. 2021;11(12):776–781.
12. Oksana T, Dmytro G. Earth's water distribution. 2021, pp. 1–14. doi:10.1007/978-3-319-70061-8_103-1
13. Okafor CO, Ude UI, Okoh FN, Eromonsele BO, Okafor CO, Ude UI et al. Safe drinking water: the need and challenges in developing countries. In: *Water Quality: New Perspectives*. 2024. doi:10.5772/intechopen.108497

14. Auma B, Musinguzi M, Ojuka E, Kigongo E, Tumwesigye R, Acup W et al. Prevalence of diarrhea and water sanitation and hygiene (WASH) associated factors among children under five years in Lira City Northern Uganda: community based study. *PLoS ONE*. 2024;19(6):e0305054. doi:10.1371/journal.pone.0305054
15. van Vliet MTH, Thorslund J, Strokal M, Hofstra N, Flörke M, Ehalt Macedo H et al. Global river water quality under climate change and hydroclimatic extremes. *Nat Rev Earth Environ*. 2023;4(10):687–702. <https://www.nature.com/articles/s43017-023-00472-3>
16. Mohanavelu A, Naganna SR, Al-Ansari N. Irrigation induced salinity and sodicity hazards on soil and ground-water: an overview of its causes, impacts and mitigation strategies. *Agriculture*. 2021;11(10):983. <https://www.mdpi.com/2077-0472/11/10/983/htm>
17. Strade E, Kalnina D, Kulczycka J. Water efficiency and safe re-use of different grades of water – topical issues for the pharmaceutical industry. *Water Resour Ind*. 2020;24:100132.
18. Datta S, Sinha D, Chaudhary V, Kar S, Singh A. *Water Pollution of Wetlands: A Global Threat to Inland, Wetland, and Aquatic Phytodiversity*. 2022; pp. 27–50. doi:10.4018/978-1-7998-9498-8.ch003
19. Hasan BMR, Islam MS, Kundu P, Mallick UK. Modeling the effects of algal bloom on dissolved oxygen in eutrophic water bodies. *J Math*. 2023(1):2335570. doi:10.1155/2023/2335570
20. Chaturvedi A, Pandey B, Yadav AK, Saroj S. An overview of the potential impacts of global climate change on water resources. In Binota Thokchom, Pengpeng Qiu, Pardeep Singh, Parameswar K. Iyer (Ed.), *Water Conservation in the Era of Global Climate Change*. Elsevier, 2021; pp. 99–120.
21. Sierra JP, Junquas C, Espinoza JC, Segura H, Condom T, Andrade M et al. Deforestation impacts on Amazon-Andes hydroclimatic connectivity. *Climate Dyn*. 2021;58:9. doi:10.1007/s00382-021-06025-y
22. Dai A, Zhao T, Chen J. Climate change and drought: a precipitation and evaporation perspective. *Curr Clim Change Rep*. 2018;4(3):301–312. doi:10.1007/s40641-018-0101-6
23. Fida M, Li P, Wang Y, Alam SMK, Nsabimana A. Water contamination and human health risks in Pakistan: a review. *Expos Health*. 2022;15(3):619–639. doi:10.1007/s12403-022-00512-1
24. Pereira MA, Marques RC. Sustainable water and sanitation for all: are we there yet? *Water Res*. 2021;207:117765.
25. Moallemi EA, Malekpour S, Hadjikakou M, Raven R, Szetey K, Ningrum D et al. Achieving the sustainable development goals requires transdisciplinary innovation at the local scale. *One Earth*. 2020;3(3):300–313. <https://www.cell.com/article/S2590332220304152/fulltext>
26. Addisie MB. Evaluating drinking water quality using water quality parameters and esthetic attributes. *Air Soil Water Res*. 2022;15. doi:10.1177/11786221221075005
27. Bonacina L, Fasano F, Mezzanotte V, Fornaroli R. Effects of water temperature on freshwater macroinvertebrates: a systematic review. *Biol Rev*. 2023;98(1):191–221. doi:10.1111/brev.12903
28. Wang P, Luo M, Liao W, Xu Y, Wu S, Tong X et al. Urbanization contribution to human perceived temperature changes in major urban agglomerations of China. *Urban Clim*. 2021;38:100910.
29. Ceschin S, Ferrante G, Mariani F, Traversetti L, Ellwood NTW. Habitat change and alteration of plant and invertebrate communities in waterbodies dominated by the invasive alien macrophyte *Lemna minuta* Kunth. *Biol Invasions*. 2020;22(4):1325–1337. doi:10.1007/s10530-019-02185-5
30. Khatib Sulaiman J, Ichwana Putra D, Rianda Y, Ekariani S. Design and implementation of a microcontroller-based water turbidity detector utilizing the nephelometric turbidity unit method. *Indones J Comput Sci*. 2023;12(5):2023–2612.
31. Scott EE, Haggard BE. Natural characteristics and human activity influence turbidity and ion concentrations in streams. *J Contemp Water Res Educ*. 2021;172(1):34–49. doi:10.1111/j.1936-704X.2021.3353.x
32. Karmanovskaya NV, Nosova OV, Galishevskaya VV. Public environmental monitoring of the quality of water bodies in Norilsk and Taimyr. *Environ Ecol Res*. 2021;9(2):45–63. <https://www.hrpub.org>
33. Dey SR, Devi P, Kumar P. Organic contaminants in aquatic environments: sources and impact assessment. In: *Metal Organic Frameworks for Wastewater Contaminant Removal*. 2023; pp. 299–317. doi:10.1002/9783527841523.ch13
34. Elzagheid M. *Water Chemistry, Analysis and Treatment: Pollutants, Microbial Contaminants*. https://books.google.co.in/books?hl=en&lr=&id=NoLIEAAQBAJ&oi=fnd&pg=PR7&dq=Water+with+a+color+level+above+15+PCU+is+often+considered+unsuitable+for+drinking+without+treatment.+Odor+in+water,+typically+caused+by+organic+decay+or+industrial+pollution,+can+be+a+warning+sign+of+contamination&ots=L_vNNsOrj8&sig=ztRuOaQz3vOJ49eXX0HqTYI6ae4&redir_esc=y#v=onepage&q&f=false
35. Abd Nasier M, Adel Abdulrazzaq K. Performance evaluation the turbidity removal efficiency of Al-Muthana water treatment plant. *J Eng*. 2022; 28(8):19.
36. Antony A, Farid M. Effect of temperatures on polyphenols during extraction. *Appl Sci*. 2022;12:2107. <https://www.mdpi.com/2076-3417/12/4/2107/htm>
37. Juncosa R, Cereijo JL, Vázquez R. Physicochemical parameters in the generation of turbidity episodes in a water supply distribution system. *Water (Switzerland)*. 2022;14(21):3383. <https://www.mdpi.com/2073-4441/14/21/3383/htm>

38. Masime SP. Water quality of Athi river and its tributaries based on selected physical-chemical parameters, heavy metals and bacterial levels. 2022. <https://41.89.164.27:8080/xmlui/handle/123456789/1752>
39. Dey S, Botta S, Kallam R, Angadala R, Andugala J. Seasonal variation in water quality parameters of Gudlavalleru Engineering College pond. *Curr Res Green Sustain Chem*. 2021;4:100058.
40. Morshed M, Hosen M, Asaduzzaman Md. A review on pH, DO and BOD of the Sitalakhya River during last four decades. *Asian J Fish Aquat Res*. 2021;14(1):25–42.
41. Plowman CQ, Trowbridge CD, Davenport J, Little C, Harman L, McAllen R. Stressed from above and stressed from below: dissolved oxygen fluctuations in Lough Hyne, a semi-enclosed marine lake. *ICES J Mar Sci*. 2020;77(6):2106–2117. doi:10.1093/icesjms/fsaa108
42. Aa I, Op A, Ujj I, Mt B. A critical review of oil spills in the Niger Delta aquatic environment: causes, impacts, and bioremediation assessment. *Environ Monit Assess*. 2022;194(11):1–25. doi:10.1007/s10661-022-10424-x
43. Bailey A, Meyer L, Pettingell N, Macie M, Korstad J. Agricultural practices contributing to aquatic dead zones. *Ecol Pract Appl Sustain Agric*. 2020;373–93. doi:10.1007/978-981-15-3372-3_17
44. Rehman JU, Ahmad N, Ullah N, Alam I, Ullah H. Health risks in different age group of nitrate in spring water used for drinking in Harnai, Balochistan, Pakistan. *Ecol Food Nutr*. 2020;59(5):462–471. doi:10.1080/03670244.2020.1737044
45. Xia Y, Zhang M, Tsang DCW, Geng N, Lu D, Zhu L et al. Recent advances in control technologies for non-point source pollution with nitrogen and phosphorous from agricultural runoff: current practices and future prospects. *Appl Biol Chem*. 2020;63(1):1–13. doi:10.1186/s13765-020-0493-6
46. Fatoki JO, Badmus JA. Arsenic as an environmental and human health antagonist: a review of its toxicity and disease initiation. *J Hazard Mater Adv*. 2022;5:100052.
47. Frisbie SH, Mitchell EJ. Arsenic in drinking water: an analysis of global drinking water regulations and recommendations for updates to protect public health. *PLoS ONE*. 2022;17(4):e0263505. doi:10.1371/journal.pone.0263505
48. Winder M, Kosztyła Z, Boral A, Kocelak P, Chudek J. The impact of iodine concentration disorders on health and cancer. *Nutrients*. 2022;14(11):2209. <https://www.mdpi.com/2072-6643/14/11/2209/htm>
49. Hung DT, Thi Cuc V, Thi Bich Phuong V, Thi Thanh Diu D, Thi Huyen Trang N, Phuong Thoa N et al. Evaluation of drinking water quality in schools in a district area in Hanoi, Vietnam. *Environ Health Insights*. 2020;14. doi:10.1177/1178630220959672
50. Cravo A, Rosa A, Jacob J, Correia C. Dissolved oxygen dynamics in Ria Formosa Lagoon (South Portugal): a real time monitoring station observatory. *Mar Chem*. 2020;223:103806.
51. Jannat JN, Khan MSI, Islam HMT, Islam MS, Khan R, Siddique MAB et al. Hydro-chemical assessment of fluoride and nitrate in groundwater from east and west coasts of Bangladesh and India. *J Clean Prod*. 2022;372:133675.
52. Mweta G, Changadeya W. Spatial and temporal dynamics of water quality in aquatic ecosystems: a review of physical, chemical and biological gnomes of some Rivers in Malawi. *Malawi J Sci Technol*. 2022;14(1):1–18. <https://www.ajol.info/index.php/mjst/article/view/229242>
53. Goshtasbi H, Atazadeh E, Fathi M, Movafeghi A. Using physicochemical and biological parameters for the evaluation of water quality and environmental conditions in international wetlands on the southern part of Lake Urmia, Iran. *Environ Sci Poll Res*. 2022;29(13):18805–18819. doi:10.1007/s11356-021-17057-6
54. Khan FM, Gupta R. Escherichia coli (*E. coli*) as an indicator of fecal contamination in groundwater: a review. *Environ Sci Eng*. 2020;225–235. doi:10.1007/978-3-030-45263-6_21
55. Khan JR, Hossain MB, Chakraborty PA, Mistry SK. Household drinking water *E. coli* contamination and its associated risk with childhood diarrhea in Bangladesh. *Environ Sci Poll Res*. 2022;29(21):32180–32189. doi:10.1007/s11356-021-18460-9
56. Chen L, Jiao J, Liu S, Liu L, Liu P. Mapping the global, regional, and national burden of diarrheal diseases attributable to unsafe water. *Front Public Health*. 2023;11:1302748. <https://washdata.org/>
57. Nugraha W D, Sarminingsih A, Alfisya B. The study of self purification capacity based on biological oxygen demand (BOD) and dissolved oxygen (DO) parameters. *IOP Conf Ser Earth Environ Sci*. 2020;448(1):012105. doi:10.1088/1755-1315/448/1/012105
58. Isiuku BO, Enyoh CE. Pollution and health risks assessment of nitrate and phosphate concentrations in water bodies in South Eastern, Nigeria. *Environ Adv*. 2020;2:100018.
59. Wang C, Zhao Y, Liu S, Xiao Q, Liang W, Song Y. Contamination, distribution, and risk assessment of antibiotics in the urban surface water of the Pearl River in Guangzhou, South China. *Environ Monit Assess*. 2021;193(2):1–14. doi:10.1007/s10661-021-08887-5
60. Pinto I, Rodrigues S, Lage OM, Antunes SC. Assessment of water quality in Aguieira reservoir: ecotoxicological tools in addition to the water framework directive. *Ecotoxicol Environ Saf*. 2021;208:111583.

61. Brain RA, Prosser RS. Human induced fish declines in North America, how do agricultural pesticides compare to other drivers? *Environ Sci Pollut Res.* 2022;29(44):66010–66040. doi:10.1007/s11356-022-22102-z
62. Raimi MO, Abiola I, Alima O, Omini DE. Exploring how human activities disturb the balance of biogeochemical cycles: evidence from the carbon, nitrogen and hydrologic cycles. *Res World Agric Econ.* 2021;2(3):23–44. <https://papers.ssrn.com/abstract=3896054>
63. Stephens GL, Slingo JM, Rignot E, Reager JT, Hakuba MZ, Durack PJ et al. Earth's water reservoirs in a changing climate. *Proc R Soc A.* 2020;476(2236). doi:10.1098/rspa.2019.0458
64. Al A'assam A, Ahamd MW. Photonic cloning of seas and oceans. *J Phys Conf Ser.* 2021;2114(1):012019. doi:10.1088/1742-6596/2114/1/012019
65. Sztékler K, Kalawa W, Bujok T, Boruta P, Radomska E, Mika L et al. Hybrid desalination system for Baltic Sea water: a preliminary study. *Desalination.* 2024;574:117269.
66. Islam Md S. Groundwater: sources, functions, and quality. In: *Hydrogeochemical Evaluation and Groundwater Quality.* 2023; pp. 17–36. doi:10.1007/978-3-031-44304-6_2
67. Wasko C, Westra S, Nathan R, Orr HG, Villarini G, Villalobos Herrera R et al. Incorporating climate change in flood estimation guidance. *Philos Trans R Soc A.* 2021;379:2195. doi:10.1098/rsta.2019.0548
68. Riedel T, Weber TKD. Review: the influence of global change on Europe's water cycle and groundwater recharge. *Hydrogeol J.* 2020;28(6):1939–1959. doi:10.1007/s10040-020-02165-3
69. Mishra RK. Fresh water availability and its global challenge. *BrJ Multidiscip Adv Stud.* 2023;4(3):1–78. <https://bjmas.org/index.php/bjmas/article/view/455>
70. Codur AM. Water : economics and policy. *Environ Nat Resour Econ.* 2021;575–610.
71. Patle GT. Managing groundwater resources and its quality for sustainable development of agriculture. In: *Advances in Water Management under Climate Change.* 2023; pp. 53–65. doi:10.1201/9781003351672-4
72. Hunt KMR, Turner AG, Shaffrey LC. The impacts of climate change on the winter water cycle of the western Himalaya. *Clim Dyn.* 2020;55(7–8):2287–2307. doi:10.1007/s00382-020-05383-3
73. Garcia-Soto C, Cheng L, Caesar L, Schmidtko S, Jewett EB, Cheripka A et al. An overview of ocean climate change indicators: sea surface temperature, ocean heat content, ocean ph, dissolved oxygen concentration, arctic sea ice extent, thickness and volume, sea level and strength of the AMOC (Atlantic Meridional Overturning Circulation). *Front Mar Sci.* 2021;8:642372. www.frontiersin.org
74. D'Odorico P, Chiarelli DD, Rosa L, Bini A, Zilberman D, Rulli MC. The global value of water in agriculture. *Proc Natl Acad Sci USA.* 2020;117(36):21985–21993. doi:10.1073/pnas.2005835117
75. Parvaze S, Kumar R, Khan JN, Parvaze S. Climate change, drought, and water resources. In: *Integrated Drought Manag: Assessment and Spatial Analyses in Changing Climate.* 2023, Vol. 1. pp. 541–567. doi:10.1201/9781003276555-27
76. Molden DJ, Shrestha AB, Immerzeel WW, Maharjan A, Rasul G, Wester P et al. The great glacier and snow-dependent rivers of Asia and climate change: heading for troubled waters. *Water Resour Dev Manag.* 2022;223–250. doi:10.1007/978-981-16-5493-0_12
77. Brunner MI. Floods and droughts: a multivariate perspective. *Hydrol Earth Syst Sci.* 2023;27(13):2479–2497.
78. Gehrels R, Garrett E. Rising sea levels as an indicator of global change. In Trevor Letcher (Ed.), *Climate Change: Observed Impacts on Planet Earth*, Third Edition, 2021; pp. 205–217. South Africa, Elsevier.
79. Wang X, Liu L. The impacts of climate change on the hydrological cycle and water resource management. *Water.* 2023;15(13):2342. <https://www.mdpi.com/2073-4441/15/13/2342/html>
80. Gavrilescu M. Water, soil, and plants interactions in a threatened environment. *Water.* 2021;13(19):2746. <https://www.mdpi.com/2073-4441/13/19/2746/html>
81. Hobbie SE, Grimm NB. Nature-based approaches to managing climate change impacts in cities. *Philos Trans R Soc B.* 2020;375:1794. doi:10.1098/rstb.2019.0124
82. Li X, Zhang Y, Li Z, Wang R. Response of the groundwater environment to rapid urbanization in Hohhot, the provincial capital of western China. *J Hydrol.* 2021;603:127033.
83. Kagawa A. Foliar water uptake as a source of hydrogen and oxygen in plant biomass. *Tree Physiol.* 2022;42(11):2153–73. doi:10.1093/treephys/tpac055
84. de Brito Gomes W, Correia FWS, Capistrano VB, Veiga JAP, Vergasta LA, Chou SC et al. Water budget changes in the Amazon basin under RCP 8.5 and deforestation scenarios. *Clim Res.* 2020;80(2):105–120. <https://www.int-res.com/abstracts/cr/v80/n2/p105-120/>
85. Scanlon BR, Fakhreddine S, Rateb A, de Graaf I, Famiglietti J, Gleeson T et al. Global water resources and the role of groundwater in a resilient water future. *Nat Rev Earth Environ.* 2023;4(2):87–101. <https://www.nature.com/articles/s43017-022-00378-6>

86. Wu B, Tian F, Zhang M, Piao S, Zeng H, Zhu W et al. Quantifying global agricultural water appropriation with data derived from earth observations. *J Clean Prod.* 2022;358:131891.
87. Seneviratne SI, Zhang X, Adnan M, Badi W, Dereczynski C, Luca A Di et al. Weather and climate extreme events in a changing climate. In: *Climate Change 2021: The Physical Science Basis*. IPCC Sixth Assessment Report. 2021, pp. 1513–1766.
88. Maliva R. Intergovernmental panel on climate change and global climate change projections. Book chapter in *Climate Change and Groundwater: Planning and Adaptations for a Changing and Uncertain Future*. WSP Methods in Water Resources Evaluation Series No. 6.2021; pp. 71–88. doi:10.1007/978-3-030-66813-6_4
89. Nsabiyeze A, Ma R, Li J, Luo H, Zhao Q, Tomka J et al. Tackling climate change in agriculture: a global evaluation of the effectiveness of carbon emission reduction policies. *J Clean Prod.* 2024;468:142973.
90. Yang D, Yang Y, Xia J. Hydrological cycle and water resources in a changing world: a review. *Geograph Sustainab.* 2021;2(2):115–122.
91. Sun J, Peng Z, Zhu ZR, Fu W, Dai X, Ni BJ. The atmospheric microplastics deposition contributes to microplastic pollution in urban waters. *Water Res.* 2022;225:119116.
92. Wang S, Zheng W, Currell M, Yang Y, Zhao H, Lv M. Relationship between land-use and sources and fate of nitrate in groundwater in a typical recharge area of the North China Plain. *Sci Total Environ.* 2017;609:607–620.
93. Gupta R, Kumar Sharma P. A review of groundwater-surface water interaction studies in India. *J Hydrol.* 2023;621:129592.
94. Srinivas R, Singh AP, Dhadse K, Garg C. An evidence based integrated watershed modelling system to assess the impact of non-point source pollution in the riverine ecosystem. *J Clean Prod.* 2020;246:118963.
95. Vilmin L, Bouwman AF, Beusen AHW, van Hoek WJ, Mogollón JM. Past anthropogenic activities offset dissolved inorganic phosphorus retention in the Mississippi River basin. *Biogeochemistry.* 2022;161(2):157–69. doi:10.1007/s10533-022-00973-1
96. Palakkeel Veetil D, Arriagada EC, Mulligan CN, Bhat S. Filtration for improving surface water quality of a eutrophic lake. *J Environ Manage.* 2021;279:111766.
97. Motlagh AM, Yang Z, Saba H. Groundwater quality. *Water Environ Res.* 2020;92(10):1649–1658. doi:10.1002/wer.1412
98. Verma A, Sharma A, Kumar R, Sharma P. Nitrate contamination in groundwater and associated health risk assessment for Indo-Gangetic Plain, India. *Groundw Sustain Dev.* 2023 Nov 1;23:100978.
99. Gaaloul N, Eslamian S. Groundwater quality in arid environments. In: *Clean Water and Sanitation.* 2022; pp. 260–272. doi:10.1007/978-3-319-95846-0_132
100. Lucas LV, Deleersnijder E. Timescale methods for simplifying, understanding and modeling biophysical and water quality processes in coastal aquatic ecosystems: a review. *Water.* 2020;12(10):2717. <https://www.mdpi.com/2073-4441/12/10/2717/htm>
101. Day J, Goodman R, Chen Z, Hunter R, Giosan L, Wang Y. Deltas in arid environments. *Water.* 2021;13(12):1677. <https://www.mdpi.com/2073-4441/13/12/1677/htm>
102. Gautam AS, Tripathi SN, Joshi A, Mandariya AK, Singh K, Mishra G et al. First surface measurement of variation of Cloud Condensation Nuclei (CCN) concentration over the Pristine Himalayan region of Garhwal, Uttarakhand, India. *Atmos Environ.* 2021;246:118123.
103. Zhou S, Yang J, Wang WC, Zhao C, Gong D, Shi P. An observational study of the effects of aerosols on diurnal variation of heavy rainfall and associated clouds over Beijing-Tianjin-Hebei. *Atmos Chem Phys.* 2020;20(9):5211–5229.
104. Shammas NK, Wang LK, Wang MHS. Sources, chemistry and control of acid rain in the environment. In: *Handbook of Environment and Waste Management*, edited by Hung YT, Wang LK, Shammas NK. 2020; pp. 1–26.
105. Sivalingam S, Vishal G, Anush B. Environmental and health effects of acid rain. In: *Health and Environmental Effects of Ambient Air Pollution: Air Pollution, Human Health, and the Environment*, edited by Dehghani MH, Karri RR, Vera T, & Hassan SK. 2024; Vol. 1, pp. 91–107.
106. Vishwakarma A, Shukla SK, Tripathi VK, Dwivedi CS, Jha SK, Tripathi A. Effects of acid mine drainage on hydrochemical properties of groundwater and possible remediation. In: *Groundwater Geochemistry: Pollution and Remediation Methods.* 2021; pp. 232–264. doi:10.1002/9781119709732.ch12
107. Mishra RK. The effect of eutrophication on drinking water. *Br J Multidiscip Adv Stud.* 2023;4(1):7–20. <https://bjmas.org/index.php/bjmas/article/view/260>
108. Day JW, Conner WH, DeLaune RD, Hopkinson CS, Hunter RG, Shaffer GP et al. A review of 50 years of study of hydrology, wetland dynamics, aquatic metabolism, water quality and trophic status, and nutrient biogeochemistry in the barataria basin, mississippi delta—system functioning, human impacts and restoration approaches. *Water.* 2021;13:642. <https://www.mdpi.com/2073-4441/13/5/642/htm>
109. Ahmed AKA, El-Rawy M. The impact of aquifer recharge on groundwater quality. 2024; pp. 207–222. doi:10.1007/978-3-031-58764-1_10

110. Ramalingam S, Panneerselvam B, Shunmuga ., Kaliappan P. Effect of high nitrate contamination of ground-water on human health and water quality index in semi-arid region, South India. *Arab J Geosci.* 2022;15(3):1–14. doi:10.1007/s12517-022-09553-x
111. Allan RP, Barlow M, Byrne MP, Cherchi A, Douville H, Fowler HJ et al. Advances in understanding large-scale responses of the water cycle to climate change. *Ann NY Acad Sci.* 2020;1472(1):49–75. doi:10.1111/nyas.14337
112. Radhapyari K, Datta S, Dutta S, Barman R. Impacts of global climate change on water quality and its assessment. In: *Water Conservation in the Era of Global Climate Change*, edited by Thokchom B, Qiu P, Singh P, Iyer, PK. 2021; pp. 229–275.
113. Gleeson T, Wang-Erlandsson L, Porkka M, Zipper SC, Jaramillo F, Gerten D et al. Illuminating water cycle modifications and Earth system resilience in the Anthropocene. *Water Resour Res.* 2020;56(4):e2019WR024957. doi:10.1029/2019WR024957
114. Musie W, Gonfa G. Fresh water resource, scarcity, water salinity challenges and possible remedies: a review. *Heliyon.* 2023;9(8). <https://www.cell.com/article/S2405844023058930/fulltext>
115. Khilchevskiy V, Karamushka V. Global water resources: distribution and demand. 2021;1–11. doi:10.1007/978-3-319-70061-8_101-1
116. Zahoor I, Mushtaq A. Water pollution from agricultural activities: a critical global review. *IJCBS.* 2023;23(1):2023.
117. Feng L, Wang Y, Hou X, Qin B, Kuster T, Qu F et al. Harmful algal blooms in inland waters. *Nat Rev Earth Environ.* 2024;5(9):631–644. <https://www.nature.com/articles/s43017-024-00578-2>
118. Arias A, Botte S. Oxygen depletion in coastal waters and the open ocean : hypoxia and anoxia cases and consequences for biogeochemical cycling and marine life. 2020; pp. 41–67.
119. Rath S. Microbial contamination of drinking water. In: *Water Pollution and Management Practices.* 2021; pp. 1–17. doi:10.1007/978-981-15-8358-2_1
120. Fujisaki-Manome A, Anderson EJ, Kessler JA, Chu PY, Wang J, Gronewold AD. Simulating impacts of precipitation on ice cover and surface water temperature across large lakes. *J Geophys Res Oceans.* 2020;125(5):e2019JC015950. doi:10.1029/2019JC015950
121. Allison I, Paul F, Colgan W, King M. Ice sheets, glaciers, and sea level. In: *Snow and Ice-Related Hazards, Risks, and Disasters.* 2021; pp. 707–740.
122. Jain R. The urban transformation: issues and challenges. In: *Urban Growth and Environmental Issues in India.* 2021; pp. 17–34. doi:10.1007/978-981-16-4273-9_2
123. Singh N, Poonia T, Siwal SS, Srivastav AL, Sharma HK, Mittal SK. Challenges of water contamination in urban areas. In: Sughosh Madhav, Abhishek Kumar Bhardwaj, Eugenia Valsami-Jones, Arun Lal Srivastav, eds. *Urban Water Crisis and Management - Strategies for Sustainable Development*, Elsevier. 2022; Vol. 6, pp. 173–202.
124. Im KH, Behbahani S, Iseley DT. The impact of near-failing grades of water infrastructure affecting end customers. In: *Pipelines 2022: Planning and Design - Proceedings of Sessions of the Pipelines 2022 Conference*, Vol. 4. 2022; pp. 102–11. doi:10.1061/9780784484302.012
125. Koop SHA, Grison C, Eisenreich SJ, Hofman J, van Leeuwen KJ. Integrated water resources management in cities in the global solutions. *Sustain Cities Soc.* 2022;86:104137.
126. Castro-Muñoz R, González-Melgoza LL, García-Depraet O. Ongoing progress on novel nanocomposite membranes for the separation of heavy metals from contaminated water. *Chemosphere.* 2021;270:129421.
127. Ahmed SF, Mehejabin F, Momtahin A, Tasannum N, Faria NT, Mofijur M et al. Strategies to improve membrane performance in wastewater treatment. *Chemosphere.* 2022;306:135527.
128. Collins R, Johnson D, Crilly D, Rickard A, Neal L, Morse A et al. Collaborative water management across England: an overview of the catchment based approach. *Environ Sci Policy.* 2020;112:117–125.
129. Imran LB, Latif RMA, Farhan M, Aldabbas H. Smart city based autonomous water quality monitoring system using WSN. *Wirel Pers Commun.* 2020;115(2):1805–1820. doi:10.1007/s11277-020-07655-x
130. Hamel P, Tan L. Blue–green infrastructure for flood and water quality management in Southeast Asia: evidence and knowledge gaps. *Environ Manag* 2021;69(4):699–718. doi:10.1007/s00267-021-01467-w
131. Koh R, Babel MS, Shinde VR, Mendoza G. Towards climate resilient municipal water supply in Bangkok: a collaborative risk informed analysis. *Clim Risk Manag.* 2022;35:100406.
132. Tantoh HB, Simatele DM, Ebhuoma E, Donkor K, McKay TJM. Towards a pro-community-based water resource management system in Northwest Cameroon: practical evidence and lessons of best practices. *Geo J.* 2021;86(2):943–961. doi:10.1007/s10708-019-10085-3
133. Post GB. Recent US state and federal drinking water guidelines for per- and polyfluoroalkyl substances. *Environ Toxicol Chem.* 2021;40(3):550–563. doi:10.1002/etc.4863
134. Sishodia RP, Ray RL, Singh SK. Applications of remote sensing in precision agriculture: a review. *Remote Sens.* 2020;12:3136. <https://www.mdpi.com/2072-4292/12/19/3136/htm>
135. Getahun S, Kefale H, Gelaye Y. Application of precision agriculture technologies for sustainable crop production and environmental sustainability: a systematic review. *Sci World J.* 2024;(1):2126734. doi:10.1155/2024/2126734

Major Water Pollutants and Contaminants

2

Identification and Classification

Fatima Zahra Benbrahim, El Houssain Bouichou,
Mohammed Zouini, Yasmine Azzouzi,
Khaoula Boumais, and Ilias Mouallif

2.1 INTRODUCTION

Water is a resource that has many uses: recreation, transportation, hydroelectric power, agriculture, domestic, industrial, and commercial use. Water is an important element for life, individuals and society, as it is a source of energy and is responsible for all productive activities around us.

Water is also the carrier of all forms of life and affects our health, lifestyle, and economic well-being. As individuals, we use water for sanitation, drinking, and many other needs, and we pay for the water utilities that supply us.

Although water flows from our taps throughout the day, we often take for granted the amount of fresh water available on Earth, when in fact it is the dominant factor in maintaining the ecological balance and its substitution would not be possible, as it ensures the viability of the surrounding environment.

Water is an important part of the life-sustaining system. No one can live or even dream of living without water. Most of our water bodies are polluted due to industrial growth, urbanization, and man-made problems resulting mainly from population growth. Poor hygiene conditions and contamination of drinking water due to human activities and natural phenomena pose serious health problems. The main sources of water pollution are sewage and other wastes, industrial effluents, agricultural discharges, and industrial waste from the chemical industries, fossil fuel power plants, and nuclear power plants. They create a huge problem of water pollution that makes the water unfit for drinking, agriculture, and aquatic life. More than 2.6 billion people, or 40% of the world's population, lack basic sanitation facilities and more than one billion people still use unsafe water sources. As a result, thousands of children die every day from diarrhea and other water, sanitation, and hygiene-related diseases, and many people suffer and are weakened by the disease.

2.2 TYPES OF WATER POLLUTION

Contamination of natural water bodies, such as lakes, rivers, wetlands in the ocean, reservoirs, and streams, is known as water pollution. Only 1.1% of the Earth's hydrosphere is liquid freshwater; the remaining 96% is made of salt water from the oceans [1]. We currently face an urgent need to protect it from pollution, which is the most essential natural component for forming the environment and maintaining the diversity of life on Earth [2].

However, pollutants can be radioactive, microbiological, pathogenic, chemical, or physical. When pollutants are discharged into water bodies, either directly or indirectly, without sufficient treatment to remove hazardous substances, water pollution occurs. Besides damaging the natural biological communities surrounding contaminated water reservoirs, water pollution also negatively impacts ecosystems (the plants and animals that live in these water bodies) [3].

Surface waters are increasingly vulnerable to contamination and pollution due to extensive industrialization, rapid urbanization, and inadequate sanitation [2]. This pollution can be caused by natural or human-related activities [4]. It poses harmful effects on human health by inducing hormonal changes, expediting the aging process, and consequently leading to the early onset of health issues related to aging.

Water pollutants can generally be classified into three types: chemicals (organic and inorganic), physical, and biological agents, depending on the source of contamination. Additionally, they can be grouped into two categories based on their origin: (a) point sources and (b) diffuse sources.

2.2.1 Point Source of Pollution

Pollutants that enter water from a single, identifiable source of human activity are called point sources of pollution. According to [5], the following factors generally affect water quality: increased sediment runoff or soil erosion caused by changes in land use, mining, livestock raising, wastewater generation, and disposal (e.g., industrial, municipal, and agricultural). Examples include pipes attached to a factory, oil spills from an oil tanker, and effluent from industries. Point sources of pollution such as wastewater effluent (municipal and industrial) and storm sewer discharges primarily affect the nearby regions [3,6]. These discharges can harm aquatic ecosystems and affect forest tree species surrounding the water body.

In addition, the inversion of investigative data can be used to identify the locations, intensities, and pathways of pollution sources, thus recreating the processes of migration and transformation of pollutants in groundwater [7].

As a result, pollutants can contaminate our drinking water sources, reduce oxygen levels that can kill fish and other wildlife, accumulate in the tissues of the fish we catch and eat in lakes, reduce the beauty of the water, and even spread to the immediate environment by causing damage to forest tree species around lakes.

2.2.2 No Source Point Pollution

Nonpoint sources of pollution are those that originate from different sources of origin and contaminants enter groundwater or surface water in many ways and enter the environment from different unidentifiable sources. Examples include runoff from agricultural fields, urban waste, etc. Sometimes, pollution that enters in one location can be observed hundreds or even thousands of miles away. This is known as transboundary pollution. One example is radioactive waste that travels across the oceans from nuclear-reprocessing plants to neighboring countries [3,6].

In urban areas, stormwater runoff is one of the major sources of nonpoint source pollution that deteriorates water quality of streams and bays. Stormwater from streets is often contaminated with vehicle oil, dust, animal droppings, soil, and sediment from construction sites, and industrial areas often have higher levels of toxins and chemicals.

In agricultural areas, nonpoint source pollution includes pesticides, fertilizers, animal manure, and soil carried into waterways by stormwater runoff. When people enter river banks, they pollute the water and accelerate erosion. Agriculture often has a significant impact on water quality. Chemicals such as herbicides, pesticides, and fertilizers can leach into water bodies or groundwater, especially if applied in large quantities.

Diffuse pollution, also known as natural pollution, has a greater impact than man-made pollution or point source pollution. It impacts water sources such as surface water and groundwater and can be irregular or accidental [8].

2.3 IDENTIFICATION OF WATER CONTAMINANTS

Methods for monitoring and analyzing water pollution play a crucial role in assessing the quality of source water and ensuring the safety of drinking water. Various studies presented in this chapter highlight the importance of regular monitoring of groundwater quality by analyzing key parameters such as total dissolved solids, pH, chlorides, hardness, sulfates, and fluorides. In addition, industrial effluent and wastewater analysis can identify pollutants and monitor their concentrations over time. Water quality monitoring studies in different regions provide valuable information on the potability of drinking water sources, guiding decision-making processes for water resources management. By implementing pretreatment processes and environmental management plans, it is possible to control and mitigate the impact of water pollution, safeguarding the health and well-being of communities that rely on clean water sources.

2.3.1 Water Quality Testing

Water quality analysis is a critical process that involves the analysis of various physical, chemical, and biological parameters to assess the safety and suitability of water for different uses such as drinking, irrigation, and industrial use. Commonly tested parameters during water quality analysis are pH, turbidity, dissolved oxygen, total dissolved solids, total suspended solids, conductivity, alkalinity, hardness, nutrients (nitrogen and phosphorus), heavy metals, and microbial contaminants (bacteria, viruses, and parasites).

Analytical methods may vary depending on the parameter being analyzed. For example, pH can be measured using a pH meter, turbidity is assessed using a turbidity meter, and microbial contaminants are detected by methods such as membrane filtration or culture techniques. Chemical parameters such as heavy metals are usually analyzed by spectrophotometry or atomic absorption spectroscopy.

To assess this quality, water quality indices (WQIs) are widely used. They are crucial tools for concisely assessing and communicating the state of water quality from complex data on multiple parameters [9]. They are based on physical, chemical, and biological parameters, which are collected from water samples and transformed into a common scale to facilitate their interpretation [10]. These indices simplify the data into a single score, making it easier for agencies and the public to monitor water quality. The process begins with the selection of the most relevant parameters, which are then converted to a common scale before being weighted according to their impact on water quality, and the values are aggregated to form a single index that typically ranges from 0 (poor quality) to 100 (excellent quality) [11].



FIGURE 2.1 Key phases in the development of the EQI.

This method allows not only a rapid assessment but also an efficient temporal and spatial comparison of water quality between different sites and at different times.

The water quality index (WQI) development involves several phases that combine different water quality parameters into a single, comprehensible figure. These phases are essential for assessing the overall quality of a water source based on several parameters. As shown in Figure 2.1, the main phases of Environmental Quality Index (EQI) development are:

1. **Parameter selection:** This first step is to select the water quality parameters that are most relevant to the assessment. Parameters are usually selected based on their impact on water quality and may include factors such as oxygen levels, pH, turbidity, biochemical oxygen demand, etc. [12]
2. **Transform raw data into a common scale:** As the parameters exhibit different units and scales, it is essential to transform them into a uniform scale. This ensures that each parameter can be evaluated in a comparable way, which usually involves normalization or standardization of the data [13].
3. **Weight allocation:** Not all parameters have the same impact on water quality. In this phase, weights are assigned to each parameter based on their relative importance to overall water quality. These weights are usually determined by experts or statistical methods [14].
4. **Aggregation of subindex values:** The final phase of the EQI development is the aggregation of weighted subindices into a single index value. This aggregate value provides a comprehensive assessment of water quality, typically ranging from 0 (poor quality) to 100 (excellent quality), making it easier to interpret and use for water quality management [11,15].

These phases ensure that the EQI is a robust and reliable tool for summarizing complex and varied water quality data in an easily understandable format, which contributes to effective water quality management and decision-making.

Figure 2.2 shows the trend of developing WQI research over time. This is a positive trend showing that these EQIs are becoming more significant and relevant in the assessment and management of water resources. Between the 1970s and the mid-1990s, the number of EQI research publications remained relatively constant, reflecting the early stages of development and the limited application of the concept. Between the mid-1990s and the 2010s, there was a moderate increase in the volume of research publications

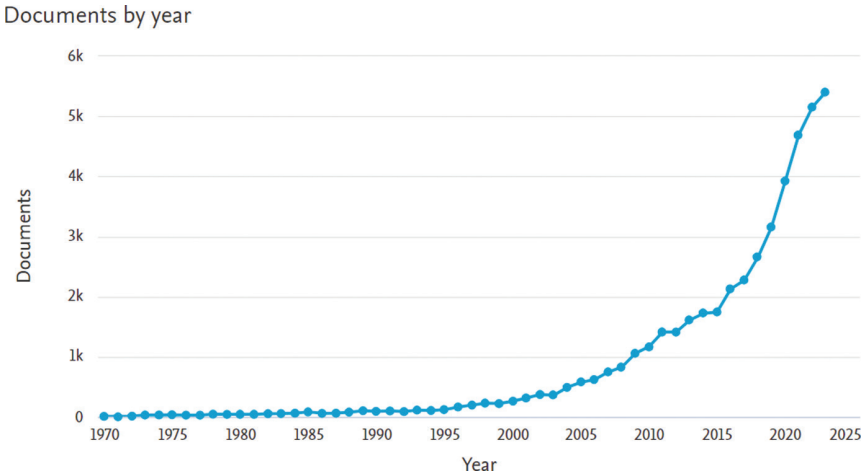


FIGURE 2.2 Progress in water quality index (WQI) research.

available on EQI. This would indicate a growing recognition of the value of EQIs as a tool for assessing and managing water quality. It is likely that during this phase, studies were undertaken to apply EQI to rivers, lakes, groundwater, and coastal areas. In addition, new EQI models have been developed and existing models have been adapted to specific regions or water uses, likely leading to a rise in research activities.

From 2010 to the present, the exponential increase in numbers shown in the graph indicates that the number of research papers on EQI is increasing very rapidly, marking a peak in interest and activity in the field. This rapid expansion can be attributed to several reasons, including increased awareness of environmental issues, general awareness of environmental degradation, and concerns about human health and pollution of aquatic ecosystems. These factors have driven the demand for effective water quality assessment tools, such as WQIs.

2.3.2 Remote Sensing Technologies

The integration of remote sensing technologies has been a major step forward for EQI. These technologies provide a comprehensive and continuous way to monitor water bodies over large areas, allowing for real-time data collection and faster response to pollution incidents [16,17]. For example, satellite imagery and aerial photography are used to track algal blooms, sediment transport, and dispersion of pollutants in surface waters, which are critical to maintaining water quality [18].

In addition, advances in geographic information systems (GIS) and remote sensing have facilitated the analysis of spatial and temporal variations in water quality, thereby improving the accuracy of EQIs. These technologies are particularly effective in hard-to-reach areas, providing critical data that informs water management policies and practices [19,20].

The evolution of EQI now encompasses high-tech surveillance methods that extend traditional surveillance capabilities. This fusion of technology and environmental science heralds a new era of precision in water quality management, ensuring that water remains a safe and sustainable resource for all [21,22].

2.3.3 Water Contamination

Cases of water contamination often reveal the complex interaction between human activities and the natural environment. For example, the intensification of agriculture and industrialization has increased the discharge of nitrates, phosphates, and other chemicals into waterways, leading to eutrophication phenomena

that degrade water quality and harm aquatic ecosystems [10]. Similarly, urban areas contribute to water pollution through urban runoff that carries various pollutants, such as heavy metals and hydrocarbons, to rivers and lakes [19].

Responses to these contamination challenges include the development of more advanced and efficient water treatment methods. For example, the increased use of technologies such as man-made wetlands to filter pollutants from wastewater before they reach natural waterways [20]. In addition, regulatory policies have been strengthened to limit the release of pollutants into the environment, requiring industries to treat their wastewater to more stringent standards.

Water quality monitoring programs have also been scaled up, allowing for early detection of problems and a more effective response to protect public health and aquatic ecosystems. These efforts are complemented by public awareness campaigns on sustainable water management practices and the impacts of water pollution, thereby strengthening the collective capacity to prevent and respond to contamination incidents [16].

2.4 IMPACT ON THE ENVIRONMENT

2.4.1 Effects on Aquatic Ecosystems

Human activities leave a significant footprint on aquatic ecosystems, compromising water quality and disrupting the delicate balance of life in these environments. WQIs are valuable tools for assessing the cumulative impact of pollution on marine and freshwater ecosystems. In marine environments, EQIs reveal the adverse effects of eutrophication, chemical contamination, and habitat modification. Excess nutrients, which often come from agricultural runoff and sewage discharges, lead to algal blooms and oxygen depletion, creating dead zones where marine life is threatened [23]. Toxic contaminants, such as heavy metals and pesticides, accumulate in organisms, leading to reproductive problems and mortality [24]. Physical changes to habitats, such as coral reefs and seagrass beds, further reduce biodiversity and ecosystem functionality. Similarly, freshwater ecosystems suffer from pollution-induced food web disturbances, the loss of biodiversity, and increased susceptibility to disease. High ion concentrations and changes in species composition disrupt trophic interactions and ecosystem stability [25]. Declines in water quality, as reflected in EQIs, are often correlated with decreases in species diversity [26]. In addition, pollution weakens the immune systems of freshwater organisms, making them more vulnerable to disease. EQIs play a critical role in managing these impacts by identifying areas of concern, tracking changes over time, and guiding pollution mitigation strategies. In the future, the integration of ecological indicators and advanced technologies into EQIs will be crucial for comprehensive ecosystem health assessments and proactive management interventions.

2.4.2 Implications for Human Health

The degradation of aquatic ecosystems, as revealed by WQIs, greatly impacts human health, including contamination of drinking water and the security of food sources.

Impact on food sources: EQIs incorporate parameters such as fecal coliforms, nitrates, and heavy metals, which are directly related to the safety of drinking water. Studies in areas such as Bangladesh [27] have found alarming levels of these contaminants, making water sources unsafe to drink and posing health risks to local populations. High levels of nitrates can lead to methemoglobinemia, especially in infants, while heavy metal contamination can cause

neurological disorders and organ damage. The presence of fecal coliforms indicates potential contamination with pathogens, leading to gastrointestinal illness.

Impact on food sources: Pollution of aquatic ecosystems directly impacts on the quality and safety of food sources from these environments. The bioaccumulation of toxins, such as heavy metals and persistent organic pollutants, in fish and shellfish poses a significant health risk to consumers. Research on the Maritsa River in Bulgaria [28] has found high levels of heavy metals, raising concerns about the safety of fish consumed in the river. Similarly, studies conducted on Lake Chapala in Mexico [29] have highlighted the presence of toxic metals, including zinc, which can interact with the gills of fish and have a potential impact on human health through consumption. In addition, eutrophication and harmful algal blooms can lead to the contamination of seafood with toxins, causing many diseases.

The application of EQIs is essential to identify and manage these risks to human health. By providing a comprehensive assessment of water quality, EQIs allow authorities to monitor contamination levels, implement water treatment solutions, and issue advisories or restrictions on the consumption of seafood from affected areas. Protecting the health of aquatic ecosystems is not only essential for environmental sustainability, it is also directly linked to safeguarding human well-being.

2.5 CASE STUDY: EVIDENCE FROM MOROCCO

2.5.1 Monography

Renewable water resources: The total annual volume of renewable water reaches about 22 billion m³/year, or the equivalent of 606 m³/inhabitant/year in 2023 [30,31]. It corresponds to rainfall input (140 billion m³) minus actual evapotranspiration (118 billion m³) [30,31]. About 85% of rainwater is released back into the atmosphere in the form of water vapor. Of the 22 billion m³ available, nearly 4 billion m³ infiltrate the ground and recharge groundwater (Morocco has 12 hydraulic basins that house this water) while nearly 18 billion run off into rivers and stagnant water.

Groundwater resources: Groundwater resources contribute to the supply of drinking water to the majority of rural populations, the supply of nearly 30% of urban populations and the irrigation of nearly 30% of the irrigated area. Morocco has 130 aquifers, 32 are deep aquifers and 98 are shallow aquifers.

Non-conventional water: Non-conventional water resources include the reuse of wastewater, the artificial recharge of groundwater and the production of fresh water through seawater desalination or brackish water demineralization. The National Water Strategy estimates the volume of water that can be mobilized in 2030, based on energy resources. Non-conventional water, nearly 1 billion m³ [31].

2.5.2 Water Policies in Morocco

For many decades, the Kingdom of Morocco has been committed to addressing water-related challenges by implementing effective governance of water resources. This commitment involves the adoption of well-articulated policies, the establishment of integrated management plans, the strengthening of strong and determined institutions, and the development of highly qualified human resources.

Thus, in October 2013, the delegated ministry in charge of water (MDCE) was created. Subsequently, the MDCE was replaced by the Secretariat of State for Water (SEE) in 2017, and in 2018 it was integrated into the Ministry of Equipment, Transport, Logistics and Water—Department of Water. However, many players in the water sector, including entities such as agriculture, the Interior, the National Office of Electricity and Drinking Water (ONEE), ORMVAs, Utilities, the Department of the Environment, the HCEFLCD, etc. All these organizations, in collaboration with the Department of Water, primarily focus on the development and coordination of government policy in the water sector, while emphasizing its quality.

In this context, Morocco has set up a network for monitoring the quality of water resources, with 859 monitoring stations, which cover the main rivers, dams and groundwater.

Industrial remediation in 2011, Morocco set up an industrial water depollution mechanism, within the framework of the NAP Support Programme financed by a grant from the European Union and managed by regional committees chaired by the Association for Behavioral Healthcare (ABH) and by a national committee chaired by the ministerial department in charge of the environment. The purpose of the mechanism is to encourage stakeholders to depollute industrially, to upgrade Moroccan companies to the environment and reduce their negative impacts, to finance water pollution projects, and finally, to improve water quality in the country's water basins [31].

Law 36-15 in the service of water quality: in 2016 Morocco promulgated Law 36-15 which has given particular importance to the control of the public hydraulic domain. It replaces Law 10-95 on water, which was at the origin of the management of this resource in large hydraulic basins. Thus, the said law entrusted the task of controlling the public hydraulic domain to the water police made up of government officials, in particular the government water authority, water basin agencies, and public institutions concerned. The Water is part of the public hydraulic domain composed of all continental waters, whether surface, groundwater, fresh, brackish, salt, mineral, or wastewater, as well as desalinated seawater and hydraulic works and their annexes assigned to public use. It should be noted that the public hydraulic domain is inalienable, unseizable, and imprescriptible [30].

2.5.3 Water Quality in Morocco

Dissolved oxygen (COD) and oxidizable organic matter (BOD5) are considered to be appropriate determinants of water quality according to *Rodier* 1996 [32]. They represent organic polluters. During 2016–2017, about 70% of the stations showed good to medium water quality, while 30% reported degradation, attributed mainly to a decrease in dissolved oxygen and an increase in oxidizable organic matter (BOD5, COD). Water quality is mainly degraded downstream of discharges into several basins in Morocco. For example, the Loukkos basin in Tangier, the Moulouya basin in Berkane and Oujda, the Sebou basin in Meknes and Fez, the Bouregreg and Chaouia basins in Berrechid and Settat, the Oum Er Rbia in Sidi Bennour and Benguerir, and the Tensift in Marrakech. Stations downstream of wastewater treatment facilities and industrial areas are particularly affected [31].

For mineral polluters, nitrates, total phosphorus, orthophosphate, and ammonium were determined using the methods described in *Rodier* 1996 [32]. Thus the water quality in most of the dam reservoirs is excellent to good, except the Kreima, Aride, and Moulay Youssef reservoirs, located in the Bouregreg and Oum Er Rbia hydraulic basins. The deterioration of water quality in these impoundments is mainly attributed to high levels of phosphorus [31].

Phosphorus can reach dams through agricultural runoff that carries phosphate fertilizers, industrial and also urban waste. These phosphorus fluxes contribute to the pollution of dams and can promote the bloom of algae and other harmful aquatic plants (benbrahim). Total phosphorus and orthophosphates come largely from domestic activities, followed by agricultural activities, and then industrial activities [32]. On the other hand, for groundwater, 54% of the water quality monitoring stations sampled were of good to medium quality, compared to 46% of degraded quality, and those during the hydraulic year 2016–2017. The poor quality of these waters is caused by the mineralization of groundwater due to the nature of the geological terrain and the high nitrate levels of up to 200 mg/L [31]; this value was close to the 50 mg/L in 1994 [33]. This shows the astonishing rate at which pollution is invading our waters, the number of polluters has tripled in 20 years. The main Moroccan aquifers whose water quality is degraded by high nitrate levels are the Rmel aquifer of the Loukkos basin, the Triffa and Angads aquifers of the Moulouya basin, the Fés-Méknès, Mnasra and Maâmora aquifers of the Sebou basin, the Témara and Chaouia aquifers of the Bouregreg and Chaouia basins, the Doukkala aquifer of the Oum Er Rbia basin, the Chtouka aquifer of the Souss-Massa basin. These levels are higher in market gardening areas near irrigated areas (Tadla, Gharb, Moulouya, etc.) because of agricultural intensification linked to chemical pollution by agricultural fertilizers and phytosanitary products. In addition, there is the pollution caused by the discharge of industrial wastewater into waterways, which is mostly found in the Sebou basin and the Atlantic Ocean.

For example, the Sebou concentrates organic pollution from oil mills and chromium pollution from tanneries. The Tensift basin collects heavy metals (the presence of lead, zinc and copper extraction mines). The Loukkos, Bouregreg and Souss-Massa basins remain the least affected by industrial discharges. Finally, in addition to these sources of pollution, household and industrial solid waste deposited in landfills incorporates organic pollutants, heavy metals, and other toxic pollutants that seep into the water [33].

2.5.4 Wadi Sebou Case: Surface Polluters

The Wadi Sebou is one of the most polluted wadis in Morocco due to the untreated discharges of domestic and industrial effluents from the Fez agglomeration into the natural environment. As a result, the state has set up a project to clean up this wadi with the financial assistance of the French development agency. This program includes (a) the construction of a 1.2 million population equivalent activated sludge treatment plant and (b) the implementation of an industrial depollution program covering multiple sectors (oil mills, tanneries, breweries, textile factories, etc.), and the recovery of biogas from the digestion of the plant’s sludge [31]. Following this project, tests based on methods based on Biological Diatom Index and Global Biological Index of Control and Surveillance Networks, ecological water monitoring indicators, adapted to the Moroccan context, were carried out to measure water quality. These are methods based on the analysis of macroinvertebrate populations, which make it possible to measure the ecological richness and diversity of the waters as well as the presence or absence of certain organisms chosen as indicators of different degrees of pollution in a wadi. Thus, thanks to the depollution project, the quality of the water in the wadi has improved: “an improvement in the physicochemical quality of the water in 2011 compared to that of 2007, which positively attests to the efforts made within the framework of the Sebou basin depollution programme” (Figure 2.3) [34].

Finally, following the example of the Sebou project, Morocco has set up several pollution control programs, including the establishment of new wastewater treatment plants for urban and rural agglomerations. This is part of the national liquid sanitation and wastewater reuse programs, as well as the continuation of the industrial depollution program launched in 2011.

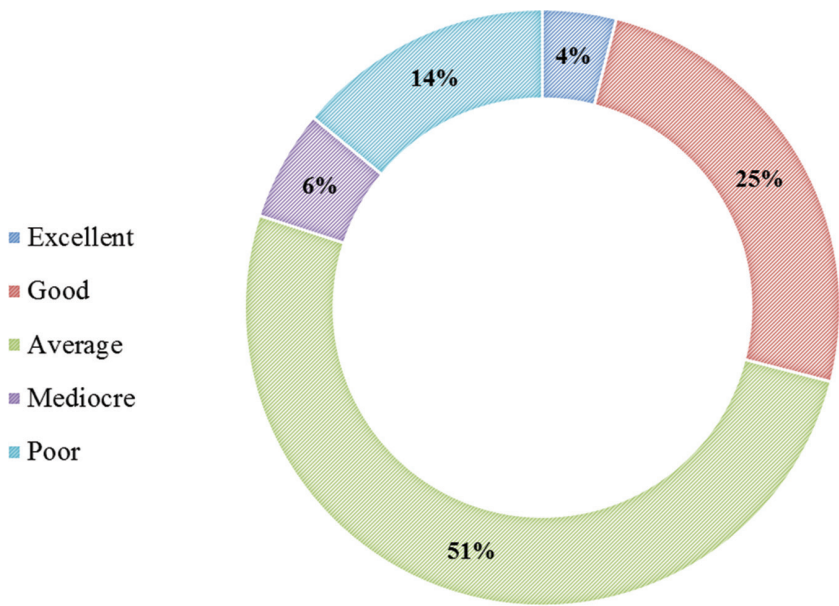


FIGURE 2.3 Quality of the water tested in the Wadi Sebou after the implementation of the depollution project.

2.6 CONCLUSION

Water is one of the most important resources on this planet for the sustenance of life and the smooth running of the various activities of human beings. Water pollution, on the other hand, is currently one of the most critical problems, with serious implications for aquatic and human life. This pollution, from industrial, agricultural, and domestic sources, threatens not only the availability and quality of water but also the possible spread of effects on biodiversity and drinking water for billions of people. The case studies illustrate the problems and progress in water resources management, referring to the example of Morocco. Morocco's initiatives, such as improving water management infrastructure and adopting strict water protection laws, illustrate how governance, through effective local and global regulations, as well as the application of cutting-edge technologies, can be crucial to reducing pollution and preserving this much-needed resource. It has therefore become inevitable that such joint efforts will be made at all levels to sustainably manage the available water. Thus, it is imperative to mention the efforts that should be made, including the implementation of policies on the sustainable management of water, the adoption of modern technology both in the treatment and monitoring of the sources that pollute it, and the education of the public on water conservation issues. Only in this way can we hope to mitigate the effects of pollution and ensure that future generations inherit an environment and water resources that are at least as healthy and abundant as those we have today.

REFERENCES

1. Dooge, J. C. I. (ed.) (2009). *Fresh Surface Water*. Eolss Publishers Company Limited, Oxfordshire.
2. Azhar, S. C., Aris, A. Z., Yusoff, M. K., Ramli, M. F., & Juahir, H. (2015). Classification of river water quality using multivariate analysis. *Procedia Environmental Sciences*, 30, 79–84.
3. Walczykowski, P., Jenerowicz, A., & Orych, A. (2013). A review on remote sensing methods of detecting physical water pollutants. In: *Proceedings of Reserech Conference Technology Discipline*, Vol. 1, pp. 125–130.
4. Uddin, M. G., Stephen, N., & Agnieszka, I. O. (2021). A review of water quality index models and their use for assessing surface water quality. *Ecological Indicators*, 122, 107218.
5. Yousefi, M., Ghoochani, M., & Hossein Mahvi, A. (2018). Health risk assessment to fluoride in drinking water of rural residents living in the Poldasht city, Northwest of Iran. *Ecotoxicology and Environmental Safety*, 148, 426–430. doi:10.1016/j.ecoenv.2017.10.057
6. Gupta, A. (2016). *Water Pollution-Sources, Effects and Control*. Pointer Publishers, Jaipur.
7. Liu, Y., Fei, Y., Li, Y., Bao, X., & Zhang, P. (2024). A review of the pollution source identification methods and remediation technologies of groundwater. *China Geology*, 7, 125–137. doi:1031035/cg2022080
8. Viman, O. V., Ioan, O., & Andrei, F. (2010). Types of water pollution: Point source and nonpoint source. *Aquaculture, Aquarium, Conservation & Legislation*, 3(5), 393–397.
9. Chaurasia, A. K., Pandey, H. K., Tiwari, S. K., Prakash, R., Pandey, P., & Ram, A. (2018). Groundwater quality assessment using Water Quality Index (WQI) in parts of Varanasi District, Uttar Pradesh, India. *Journal of Geological Society of India*, 92, 76–82. doi:10.1007/S12594-018-0955-1
10. Britto, F. B., do Vasco, A. N., Aguiar Netto, A. D. O., Garcia, C. A. B., Moraes, G. F. O., & Silva, M. G. D. (2018). Surface water quality assessment of the main tributaries in the lower São Francisco River, Sergipe. *RRRH*, 23, 6–23. doi:10.1590/2318-0331.231820170061
11. Tyagi, S., Sharma, B., Singh, P., & Dobhal, R. (2013). Water quality assessment in terms of water quality index. *American Journal of Water Resources*, 1, 34–38. doi:10.12691/AJWR-1-3-3
12. Yan, F., Liu, L., You, Z., Zhang, Y., Chen, M., Xing, & X. (2015). A dynamic water quality index model based on functional data analysis. *Ecological Indicators*, 57, 249–258. doi:10.1016/J.Ecolind.2015.05.005
13. Poonam, T., Tanushree, B., & Sukalyan, C. (2013). Water quality indices- important tools for water quality assessment: A review. *International J ournal of Advance Chemistry*, 1, 15–28. doi:10.5121/ijac.2015.1102
14. Shah, K. A., & Joshi, G. S. (2017). Evaluation of water quality index for River Sabarmati, Gujarat, India. *Applied Water Science*, 7, 1349–1358. doi:10.1007/S13201-015-0318-7

15. Tripathi, M., & Singal, S. K. (2019). Allocation of weights using factor analysis for development of a novel water quality index. *Ecotoxicology and Environmental Safety*, 183, 109510. doi:10.1016/J.ECOENV.2019.109510
16. Kumar, P. (2018). Simulation of Gomti River (Lucknow City, India) future water quality under different mitigation strategies. *Heliyon*, 4, E01074. doi:10.1016/d.heliyon.2018.e01074
17. Zhang, L. (2017). Different methods for the evaluation of surface water quality: The case of the Liao River, Liaoning Province, China. *International Review for Spatial Planning and Sustainable Development*, 5, 4–18. doi:10.14246/IRSPSD.5.4_4
18. Paun, I., Cruceru, L., Chiriac, F. L., Niculescu, M., Vasile, G. G., & Marin, N. M. (2016). Water quality indices—methods for evaluating the quality of drinking water. In: *Proceedings of the 19th INCD ECOIND International Symposium—SIMI 2016, The Environment and the Industry*, Bucharest, Romania, 13–14 October 2016, pp. 395–402. doi:10.21698/simi.2016.0055
19. Shan, W. (2011). Discussion on parameter choice for managing water quality of the drinking water source. *Procedia Environmental Sciences*, 11, 1465–1468. doi:10.1016/J.Proenv.2011.12.220
20. Mukate, S., Wagh, V., Panaskar, D., Jacobs, J. A., & Sawant, A. (2019). Development of new integrated water quality index (IWQI) model to evaluate the drinking suitability of water. *Ecological Indicators*, 101, 348–354. doi:10.1016/J.Ecolind.2019.01.034
21. Horton, R. K. (1965). An index-number system for rating water quality. *Journal of the Water Pollution Control Federation*, 37, 292–315
22. Brown, R. M., McClelland, N. I., Deininger, R. A., & Tozer, R. G. (1970). A water quality index-do we dare. *Water Sew Work*, 117, 339–343.
23. Cristable, R. M., Nurdin, E., & Wardhana, W. (2020). Water quality analysis of Saluran Tarum Barat, West Java, based on National Sanitation Foundation-Water Quality Index (NSF-WQI). *IOP Conference Series: Earth and Environmental Science*, 481, 012068. doi:10.1088/1755-1315/481/1/012068
24. Moskovchenko, D. V., Babushkin, A. G., & Yurtaev, A. A. (2020). The impact of the Russian oil industry on surface water quality (a case study of the Agan River catchment, West Siberia). *Environmental Earth Sciences*, 79, 1–21. doi:10.1007/S12665-020-09097-X
25. Vaiphei, S. P., & Kurakalva, R. M. (2021). Hydrochemical characteristics and nitrate health risk assessment of groundwater through seasonal variations from an intensive agricultural region of upper Krishna River basin, Telangana, India. *Ecotoxicology and Environmental Safety*, 213, 112073. doi:10.1016/J.ECOENV.2021.112073
26. Khan, R., Saxena, A., Shukla, S., Sekar, S., & Goel, P. (2021). Effect of COVID-19 lockdown on the water quality index of river Gomti, India, with potential hazard of faecal-oral transmission. *Environmental Science and Pollution Research*, 28, 33021–33029. doi:10.1007/S11356-021-13096-1
27. Zakir, H. M., Sharmin, S., Akter, A., & Rahman, M. S. (2020). Assessment of health risk of heavy metals and water quality indices for irrigation and drinking suitability of waters: A case study of Jamalpur Sadar area, Bangladesh. *Environmental Advances*, 2, 100005. doi:10.1016/J.envadv.2020.100005
28. Radeva, K., & Seymenov, K. (2021). Surface water pollution with nutrient components, trace metals and metalloids in agricultural and mining-affected river catchments: A case study for three tributaries of the Maritsa River, Southern Bulgaria. *Geographica Pannonica*, 25, 214–225. doi:10.5937/GP25-30811
29. Murillo-Delgado, J. O., Jimenez-Torres, H. D., Alvarez-Bobadilla, J. I., Gutierrez-Ortega, J. A., Camacho, J. B., Valle, P. F. Z., Barcelo-Quintal, I. D., Delgado, E. R., & Gomez-Salazar, S. (2021). Chemical speciation of selected toxic metals and multivariate statistical techniques used to assess water quality of tropical Mexican Lake Chapala. *Environmental Monitoring and Assessment*, 193, 1–25. doi:10.1007/S10661-021-09185-W
30. DGHM (2023). *Hydraulics in Figures*. Dir. Générale l'Hydraulique au Maroc, Ministère l'Équipement l'eau, pp. 1–12.
31. Department of Water (2018). *State of Play of the Water Sector in Morocco-CREM*. Regional Cooperation for Sustainable Management of Water Resources in the Maghreb Project, Ministry of Equipment, Transport, Logistics and Water.
32. Lalami, A. O., Merzouki, M., El Hillali, O., Maniar, S., & Koraichi, S. I. (2010). Surface water pollution in the city of Fez in Morocco: Typology, origin and consequences. *Larhyss Journal*, 9, 55–72.
33. Agoumi, A. L. I., & Debbarh, A. (2005). Water resources and watersheds of Morocco: 50 years of development (1955–2005). *Website of High Commission for Planning: The Sources of Economic Growth in Morocco*.
34. Lamhasni, N., Chillasse, L., Abba, H., El Haouat, S., & El Madani, M. (2013). Typology of surface waters in the Sebou basin by multi-approach: Correlation between global biological index of control and surveillance networks (IBG-RCS) and the physicochemical and microbiological approach. *Afrique Science*, 9(2), 35–49. <https://www.afriquescience.info>

Issues and Challenges in Water Crisis

3

Industrial and House Wastewater Treatment

Chaimae Belayouchia

3.1 INTRODUCTION

The water demand is rapidly increasing as it serves various sectors and purposes to sustain human life.

The industrial sector, a significant contributor to water pollution, consumes 20% of the world's freshwater resources and discharges more than 80% of wastewater that flows back to the environment, often containing toxic pollutants and heavy metals. However, the problem is not limited to industries; household wastewater that consumes 12%, with its thousands of waste effluents, also plays a significant role. These combined practices disrupt the ecosystem and pose severe threats to the environment and human health, underscoring the need for collective action.

Understanding the nature of pollutants and toxic chemicals present in effluents is crucial, as they have the potential to impact our planet and our health significantly. Their presence can cause adverse effects on human health; exposure to these substances can lead to respiratory problems, neurological disorders, reproductive issues, and even cancer. Moreover, they can contaminate soil, water bodies, and the air, leading to ecosystem disruption, biodiversity loss, and habitat degradation [1]. Therefore, possessing knowledge enables us to implement measures, assess their impact, and develop strategies to mitigate and prevent pollution and remediate it.

An adequate water management system can play a significant role in mitigating water crises, especially in light of issues like climate change. To achieve this, all sectors, including government, society, and the private sector, must work together to define their roles and responsibilities in developing, managing, and using water resources. Regulatory frameworks should be established to govern wastewater discharge into the environment, set limits on pollutant concentrations, and create guidelines for treatment processes and effluent quality. These measures will ensure the protection of water quality and public health.

Treating and reusing industrial and household wastewater is vital in water management efforts. It helps to protect water quality, conserve resources, promote environmental sustainability, ensure regulatory

compliance, manage risks, and safeguard public health. Effective wastewater treatment is essential for the responsible use and stewardship of water resources and supports sustainable water management goals.

3.2 MAJOR WASTEWATER CONTRIBUTORS

3.2.1 Industrial Wastewater and Its Characteristics

Industrial wastewater, which includes contaminated water from a wide array of sectors, including manufacturing, mining, steel/iron production, oil and gas fracking, industrial laundries, power plants, metal finishers, and food/beverage production, is a significant environmental concern [1].

The nature of the contaminants present in industrial wastewater depends on the factory and industry type [1].

Industrial activities release many pollutants and toxic chemicals into the environment, disrupting the natural balance and threatening all life forms, including humans. Such pollutants, heavy metals like chromium (Cr), zinc (Zn), lead (Pb), copper (Cu), iron (Fe), cadmium (Cd), nickel (Ni), arsenic (As), and mercury (Hg) that are released by paint and dye manufacturing, textile, pharmaceutical, paper, and fine chemical industries into the water cause multiple health diseases, including but not limited to organ damage and failure, cancer, and impairments in human development. Industries such as oil refineries, formaldehyde resin, and bulk drug manufacturing also produce phenol and phenolic compounds, in addition to petroleum hydrocarbons, sulfides, alkanes, high salt, nitrobenzene, and others that are generated from the petrochemicals industry. Furthermore, industrial wastewater from some industries contains a large amount of suspended matter such as solid particles, soil, gravel, sand, fibers, suspended particles, and so on [1].

The composition of industrial effluents varies depending on time, production process, product type, temperature, and so on [2]. Hence, the treatment process needs to take this variability into account and use appropriate technologies and strategies to ensure efficient treatment results [1].

3.2.2 Household Wastewater and Its Characteristics

As communities differ from one another, so do their wastes. In terms of content, quantity, and quality, this garbage changes with the number of people living in a given area, their living standards, behavior, lifestyle of inhabitants, and levels of income as well as the technical and juridical framework by which people are surrounded. Moreover, we notice that populations seem to produce waste at a rate linearly related to domestic effluents.

The wastewater produced by human household activities is mainly toilet waste from sanitary, laundry, and bathing activities, and the wastewater generated due to other household activities such as cooking. Categorically, domestic wastewater can be divided into three subtypes: blackwater, the most contaminated form consists of urine, fecal matter, toilet paper, soaps, discarded food pieces, and a lot of cleaning liquids, released from toilets, kitchen dishwashers, and sinks. Furthermore, graywater loaded with detergents, soaps, cleaning liquids, and chemicals released from baths and bathroom sinks is blackwater without fecal matter, urine, and bits of food waste. Finally, urine-only yellow water is free from additional blackwater and graywater impurities [1].

The estimated wastewater generation from clean water consumption using a factor of 70–90%, characterized by its complex mixture makes the treatment process more challenging; there are constituents arising from various human activities, consisting of organic matter, nutrients, pathogens, suspended solids, and chemical contaminants. Organic matter, including carbohydrates, proteins, fats, oils, and greases,

originates from food preparation, personal hygiene practices, and cleaning activities. Nutrients such as nitrogen and phosphorus, essential for microbial growth, are derived from human waste and the use of detergents and cleaning products. Further, pathogenic microorganisms, encompassing bacteria, viruses, and parasites, result in health risks when present in human feces and wastewater from activities like bathing and laundry. Moreover, suspended solids, comprising soil, food residues, paper products, and other debris, contribute to the physical characteristics of household wastewater. Additionally, chemical contaminants, including pharmaceuticals, personal care products, household cleaning agents, and pesticides, introduce potential hazards to the aquatic environment.

Hence, this variability in domestic wastewater characteristics is influenced by diurnal fluctuations, seasonal variations, and population dynamics, reflecting changes in water usage patterns and demographic factors; the pH levels change due to acidic or alkaline cleaning products and water source buffering capacity, while temperature variations result from ambient conditions and appliance discharges. Besides, the volume and flow rate of household wastewater depends on factors such as occupancy, water usage habits, and the adoption of water-saving technologies.

The treatment processes must target the removal or reduction of pollutants, including organic matter, nutrients, pathogens, and chemical contaminants, to comply with regulatory standards for effluent discharge or reuse.

3.3 TREATMENT TECHNOLOGIES FOR WASTEWATER

The variability of wastewater to be treated necessitates an investigation to select the adequate treatment; the testing process allows the determination of specific contaminants in wastewater and the identification of its characteristics (pH, temperature) [2], therefore enabling proactive mitigation strategies to be implemented, thus minimizing chemical usage and energy consumption, aligning with sustainability metrics and the choice of cost-effective treatment.

The wastewater treatment is a nonproductive activity, in response industries are looking for the least-cost solutions, conducting comprehensive life cycle cost analysis enables stakeholders to compare the economic feasibility and sustainability of different treatment options and make informed investment decisions [2].

Based on the intended results, the wastewater will be treated using one of these treatment systems:

- Physical treatment systems
- Chemical treatment systems
- Biological treatment systems
- The combination of these above systems [2].

3.3.1 Treatment Technologies of Wastewater

3.3.1.1 *Biological treatment method*

The most frequently used method for wastewater treatment is biological treatment. It is adaptable, cost-efficient, and highly contaminant-removal. It mainly consists of using microorganisms to feed on substances in the wastewater.

3.3.1.1.1 *The Activated Sludge Method*

The activated sludge method operates under aerobic conditions. It uses oxygen and microorganisms to biologically oxidize organic pollutants, producing a waste sludge separated by gravity and pumped back

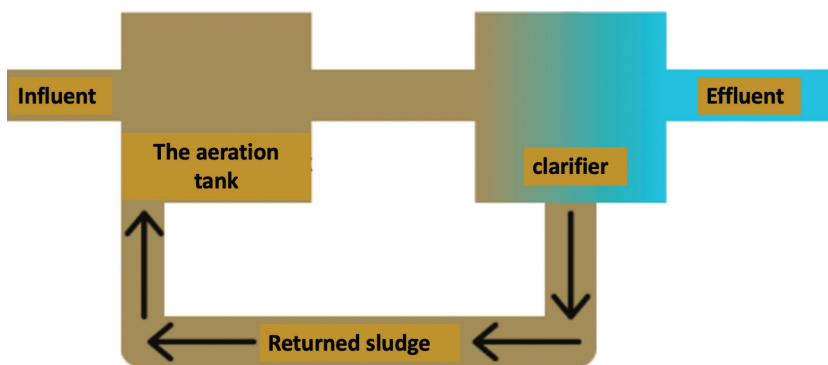


FIGURE 3.1 Activated sludge mechanism.

into the aeration tank. It removes dissolved and colloidal biochemical organic matter as well as suspended solids, phosphorus, and nutrients [2].

The activated sludge process begins with an aeration tank where air is injected into the wastewater. This is followed by a settling tank that allows the biological flocs to settle, separating the biological sludge from the clear treated water. Part of the waste sludge is recycled into the aeration tank and the remaining waste sludge is removed for further treatment and ultimate disposal [2] (Figure 3.1).

This image describes the process of treating wastewater using the activated sludge method.

3.3.1.2 The membrane bioreactor method

The combination of the activated sludge method and the membrane process is known as a membrane bioreactor (MBR) [3]. This method has gained more attention in recent years due to its high improvement of effluent quality, meeting effluent standards limits, lower post-disinfection demand, and so on.

This technology consists of the submersion of the membrane inside the biological reactor. It begins with the similar activated sludge processes, starting in the aeration tank where microorganisms convert organic matter in the wastewater into carbon dioxide, water, and microbial biomass. Therefore, the second step involves allowing the flow of treated water while preventing the passage of suspended solids, bacteria, and other microorganisms through a membrane that serves as a physical barrier. These steps create a concentrated sludge mixture known as mixed liquor suspended solids (MLSS). The MLSS contains the bacteria and biomass that were not allowed to pass through the membrane. A portion of this concentrated sludge is recycled back into the aeration tank to maintain the biological treatment process, while the excess sludge is removed from the system [3].

To effectively address the treatment needed for industrial and household wastewater, many factors should be considered including the specific characteristics of the wastewater, site-specific conditions, and project goals. Proper system design, operation, and maintenance should be taken into account to maximize the performance and efficiency of the MBRs in wastewater treatment applications (Figure 3.2).

This image illustrates the MBR process used for treating wastewater and highlights the difference between it and the activated sludge method.

3.3.1.3 The moving-bed biofilm reactor method

The moving-bed biofilm reactor (MBBR) is a wastewater biofilm-based technology used for municipal and various types of industrial wastewater treatment.

The combination of the best features of both activated sludge and biofilter processes is a key element in this process that takes place in a reactor tank after the influent enters the basin, where carriers move freely

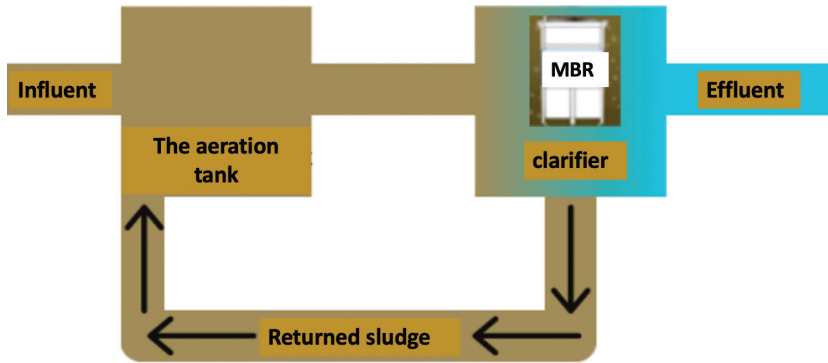


FIGURE 3.2 The MBR mechanism.

- **Carrier**

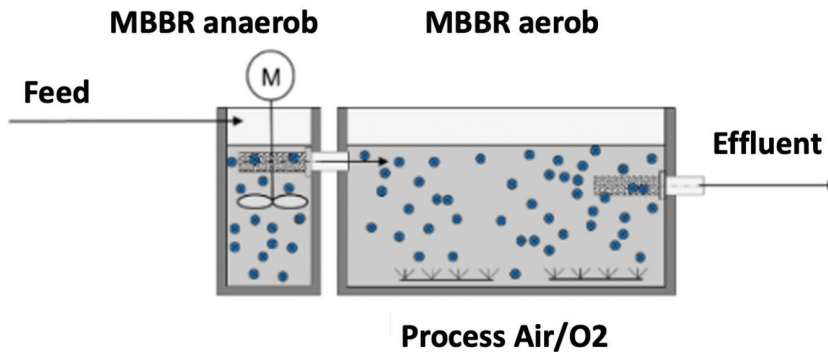


FIGURE 3.3 The MBBR mechanism [4].

to come into contact with all the waste present and efficiently decompose it. For aerobic and anaerobic processes, it is possible to use this type of reactor. Carriers, which are housing the growth of biofilms in this system, do not need to move within the tank's volume. In aerobic conditions, the carriers move by air agitation while anaerobic and anoxic processes require mechanical mixing to keep them moving [4].

The flexibility, high efficiency, and low maintenance make this process a practical alternative and a strategic move for many industries. In addition, this method minimizes or eliminates the need for biomass recirculation, a major challenge encountered in fixed-bed biofilm processes and activated sludge system (Figure 3.3).

3.3.2 Physical Treatment Method

In specific situations, where the wastewater is extremely toxic to biological treatment, the physical treatment is applied and used mostly as pretreatments. This process is essential in wastewater treatments due to its ease of operation.

Several physical treatments are developed and each method is applied based on the pollutant removal efficiency, the process complexity and operational requirements, and the operational cost. Moreover, the processes can be combined depending on the objective and desired specifications.

3.3.2.1 The oil separation

Oil separation is a technique for separating grease and suspended material from wastewater. This is achieved through gravity and surface tension. Sedimentation tanks or oil-water separation equipment are often deployed. They float the grease on the water's surface to produce an oil layer, which is then removed by a device. The said device could be a scraper or an inclined plate. Alternatively, adsorption is used. Adsorption involves adsorbent, such as activated carbon. The adsorbent adsorbs organic material from the wastewater to its surface. This is done to eradicate organic pollutants [4].

2.3.2.2 High-voltage electrical treatment

High-voltage electrical treatment denotes a method of treating suspended matter and ions in wastewater. This treatment exploits a high-voltage electric field. The electric field prompts action on these particles. Charged particles in wastewater tend to move toward the electrodes. These particles assemble on the electrodes. They can then be isolated from the solid–liquid mix. This can occur through precipitation or filtration methods [4].

2.3.2.3 The air flotation

Air flotation serves as a physical treatment method. This method separates suspended solids. It does this through the injection of fine bubbles into wastewater. This action prompts the suspended solids to agglomerate. They form floating bubbles. This technique is commonly used to extract small suspended solids and oil slicks.

In the air flotation process, air is typically employed as the bubble source. Floating bubbles are created through the fusion of air bubbles with suspended particles. These particles are less dense. Because of this, they can hover on the surface of the liquid. Afterward, a scraper apparatus or cyclone can be used. It can scrape or remove the floating bubbles. The suspended matter within these bubbles is also removed from the liquid surface. Through this process, the solids are segregated from the liquid. Air flotation equipment is available in two common forms. These are air flotation tanks and flotation settling tanks [4].

2.3.2.4 Filtration

Filtration is a prevalent physical treatment method. It employs filters or filter media to hold solid particles in wastewater. One can select filters from various types and sizes of filter media. Choices may include sand filters or activated carbon filters. Then you have centrifugal separation. This method uses centrifugal force to divide solid particles or suspended matter in wastewater. A centrifuge is the tool of choice. The rapid rotation of the centrifuge compels heavy particles to descend to the bottom of the centrifuge tube. Simultaneously, the clean liquid is ejected out [4].

3.2.3 Chemical Treatment Methods

The chemical treatment methods are less attractive for wastewater because they require substantial quantities of chemicals that are not available locally at a low price or that can have a residual effect.

3.2.3.1 Neutralization

The adjustment of the pH of wastewater using an acid or alkaline agent to bring it closer to neutral is known as neutralization. Acid and alkali chemicals can react chemically with acidic or alkaline substances in the wastewater and neutralize them. The agents used mostly in this process are sodium hydroxide and calcium hydroxide. Neutralization methods can effectively remove the problem of too high or too low acidity and alkalinity in wastewater and improve the effectiveness of subsequent treatment steps. If the concentration of acid and alkali in wastewater reaches 3%–5% or more, consideration should be given

to whether recycling should be carried out, but if the concentration is less than 2% and recycling is uneconomical, neutralization should be used [4].

3.2.3.2 Chemical precipitation

Chemical precipitation entails adding specific chemicals to wastewater. These chemicals react with dissolved impurities. As a result insoluble salt precipitates form. This procedure significantly reduces the concentration of dissolved impurities in the wastewater, facilitating their extraction.

In the context of phosphorus extraction certain chemicals are introduced. These create insoluble precipitates from phosphate and calcium, iron, or aluminum salts. They are then segregated from the wastewater via solid–liquid partitioning. Lime, aluminum sulfate ferric trichloride, iron sulfate ferrous sulfate, and ferric polyaluminum chloride are commonly used precipitants.

Throughout neutralization and precipitation, phosphate competes for ligand groups. They compete with calcium iron, or aluminum ions. This competition prompts chemical reactions and precipitation.

Hydroxide precipitation and insoluble salt precipitation are standard methods for heavy metal removal. Hydroxide precipitation or neutralization precipitation is a process. It requires adding alkali to wastewater rich in heavy metals. This action propels metal cations to form hydroxides or salts as precipitates.

The insoluble salt precipitation method makes use of precipitants. These precipitants create insoluble compounds with metal ions already present in the solution. This process catalyzes their removal or recovery. Sulfide carbonate, phosphate, and barium salt precipitation are common methods in this process [4].

3.2.3.3 Wet oxidation

Advanced oxidation technologies are also in use. Fenton oxidation and wet oxidation are prominent among them. The Fenton method hinges on Fe^{2+} as a catalyst. It promotes the decomposition of H_2O_2 . The decomposition produces $\text{OH}^\cdot$ radicals under acidic conditions.

These radicals take down pollutants like phenol and aniline compounds. Concurrently the produced Fe^{3+} aids in the removal of organic matter. It does so through coagulation. There are innovations in Fenton-like reactions on the rise. It includes the introduction of UV and visible light and the employment of alternative transition metals. These advancements enhance oxidative degradation. They also play a considerable role in the reduction of treatment costs.

Wet oxidation is also known as wet combustion. This process treats highly concentrated organic wastewater. Air is introduced to the wastewater at a high temperature and pressure. This action oxidizes and degrades organic pollutants [4].

Wet oxidation techniques operate under high temperatures and pressures. Oxygen or air serves as oxidizing agents. These agents produce carbon dioxide and water. Wet air-catalyzed oxidation uses catalysts. These catalysts achieve complete oxidation under gentler conditions. It thus reduces temperature and pressure needs. Temperature and pressure reduction in turn enhances the oxidation capacity. It also abbreviates reaction times [4].

These innovations increase the applicability of wet air catalytic oxidation technology. It is now more widely usable. The technique also leads to a decrease in equipment corrosion. Finally, it cuts down on operating costs [4].

3.4 THE REUSE AND RECYCLING OF WASTEWATER

The limited resources of freshwater, the increase in water demand, and the uncertainty related to climate change force the search for new water resources, as well as more efficient water use and the reuse of lower-value water for higher value purposes. The increasing volume of wastewater effluents within the

environment can serve as an alternative to human activities, helping to decrease freshwater demand and ensure efficient wastewater management [5].

Treating wastewater with recycling and reusing practices contributes to water quality protection, resource conservation, environmental sustainability, public health protection, and significant economic value across various domains. Despite the beneficial advantages mentioned, the adoption of such practices faces challenges that affect their implementation. Starting with public attitudes toward treated wastewater, focusing on factors influencing public perception such as education level, age, gender, nationality, housing tenure, and residential location is key to achieving public acceptance [6]. Besides, prioritizing short-term solutions over long-term sustainability by stakeholders, nonpolitical support, and the infrastructure that can be costly and complex influence the implementation of these technologies.

Public and private leaders have decisions to consider regarding the reuse of wastewater. The synergy between the public and private sectors is the best approach for the efficient and sustainable management and valorization of treated wastewater [7]. In fact, rather than being treated as trash only, wastewater will be seen more and more as a precious commodity. Research is under way to develop technologies that can recover nutrients, energy, and other valuable components from wastewater to promote a circular economy of resource use rather than waste disposal which in turn reduces the overall treatment cost. Moreover, merging the internet of things (IoT), artificial intelligence (AI), and smart sensors with it will revolutionize the wastewater industry. Real-time monitoring and controlling technologies such as this help making wastewater treatment more efficient and cost-effective [8]. Self-maintaining systems can monitor wastewater quality changes and adapt their operations, thus reducing human intervention. Furthermore, a combination of community participation and global collaboration provides an integrated approach to addressing difficulties in water, which becomes both sustainable and has worldwide impacts. Greater efficiency, adaptability, and global environmental stewardship can be achieved for the world's future wastewater management through educating and involving communities and fostering inter-state cooperation.

The reuse and recycling of wastewater include reclaiming used and treated water for irrigation [7,9]. Agriculture is one of the major consumers of water resources. Given the water scarcity issues, the reuse of wastewater is an attractive option particularly in arid and semiarid areas, as it represents a source of additional renewable and reliable water and fertilizers. The irrigation of vegetables with treated wastewater that is eaten raw is forbidden. Plots destined for irrigation with treated wastewater must not cultivate any crops except those listed below. Plots fed by treated wastewater should be situated more than 100m away from roads, residential houses, open wells, and other drinking water supply facilities. No potable water pipe connection is allowed. In addition, it can be practiced so long as the irrigation stops at least two weeks before harvesting. The fallen fruits shouldn't be harvested but destroyed instead. It is prohibited to allow direct grazing on fields irrigated using effluent to avoid pollution of livestock and hence clients themselves [7].

Table 3.1 illustrating different groups of crops that can be irrigated with treated wastewater, to ensure proper and safe practices [7].

TABLE 3.1 Groups of Crops that Can Be Irrigated with Treated Wastewater

<i>GROUPS OF CROPS THAT CAN BE IRRIGATED WITH TREATED WASTEWATER</i>	<i>LIST OF CROPS</i>
Fruit trees	Dates, grapevine, apple, peach, pear, apricot, medlar, cherry, plum, nectarine, pomegranate, fig, rhubarb, peanuts, walnuts, olive
Citrus fruits	Grapefruit, lemon, orange, mandarin, tangerine, lime, clementine
Forage crops	Berseem, forage maize, forage sorghum, vetch, alfalfa
Industrial crops	Processing tomato, pole bean, pole pea, sugar beet, cotton, tobacco, flax
Grain crops	Wheat, barley, triticale, oat
Seed production crops	Potato, bean, pea
Forage shrubs	Acacia, atriplex
Dried or industrial floral plants	Rose, iris, jasmine, marjoram, rosemary

To further improve water quality, industries can utilize treated graywater for operations that do not need potable water quality, such as cooling systems or washing facilities, in order to further enhance the quality of the water. We can use recycled wastewater for home uses, with an emphasis on household applications like bathing and laundry. It is common practice to irrigate lawns, gardens, and landscapes with treated graywater. With this use, the need for potable water in landscaping may be greatly decreased. When treated graywater is handled properly and in accordance with safety regulations, it can be used to irrigate crops, especially non-edible ones or those with little interaction with edible portions. These practices can save a significant amount of freshwater.

3.5 INNOVATIVE AND ECO-FRIENDLY APPROACHES FOR A BEST WASTEWATER MANAGEMENT

Wastewater management is one of the most effective strategies for addressing water scarcity. By implementing efficient management practices and establishing robust recycling strategies, we can significantly mitigate water shortages and promote sustainable water use.

One of the sustainable approaches to wastewater management and recycling is the constructed wetlands, that combine the effective treatment of waste effluents and enhancing biodiversity, providing wildlife habitats. It is a designed system with specific hydraulic features to ensure sufficient interaction time between wastewater and microorganisms, enabling effective treatment. The core of their functionality lies in utilizing biological processes for wastewater treatment [8]. Microorganisms living in the water column, wetland plants, and substrate break down and remove contaminants. The substrates and sediments in these artificial wetlands act as natural filters, capturing suspended particles and providing surfaces for the growth of microbial biofilms. They are used for numerous applications such as municipal treatment, industrial treatment in particular those with high organic loads or specific pollutants, agricultural runoff, stormwater management by collecting and filtering rainwater runoff, lowering the risk of flooding and improving water quality. In addition, wetlands can enhance the visual appeal of an area and offer opportunities for recreational activities such as bird watching and nature hikes, provide essential habitats for wildlife, including birds, amphibians, and aquatic species, and energy efficiency. These systems are more energy-efficient than traditional wastewater treatment facilities as they rely on natural processes and require minimal energy input [8].

Second, algae-based wastewater treatment is an eco-friendly alternative that involves growing microalgae in wastewater to remove nutrients such as nitrogen and phosphorus. This method not only purifies the water but also produces valuable biomass that can be converted into biofuels, animal feed, or fertilizer. Compared to conventional treatment techniques, algae-based systems are more energy-efficient and have a smaller carbon footprint. It utilizes the principles of photosynthesis and natural nutrient assimilation to absorb nitrogen and phosphorus from wastewater. As algae grow, they take in ammonia (NH_3) and nitrate (NO_3^-) for nitrogen removal and phosphate (PO_4^{3-}) for phosphorus absorption. The biomass accumulated acts as a nutrient sink, rich in proteins, lipids, and carbohydrates. After sufficient nutrient absorption, the algae are harvested, and the biomass is processed for various uses [8].

Last, electrocoagulation, an advanced and expensive method that works on the principles of electrochemistry and coagulation, involves passing an electric current through metal electrodes submerged in the wastewater. The process generates coagulants in situ, which destabilize and agglomerate suspended or dissolved particles, facilitating their removal. It offers efficient pollutant removal while being adaptable to various wastewater types. Its potential to be powered by renewable energy sources further underscores its role as a greener alternative in wastewater management [8].

3.6 CONCLUSION

The issues and challenges surrounding industrial and household wastewater in the context of the water crisis are undeniably intricate and multifaceted. From negative consequences on human health to the environmental deterioration of ecosystems, the implications of poor wastewater management are broad and severe.

Addressing these challenges, therefore, has to be comprehensive and necessitates collaboration with governments, industries, communities, and individuals. This must incorporate implementing rigid regulations, adopting innovative technologies, and promoting sustainable practices to offset pollution and conserve water resources.

In addition, high levels of awareness and accountability for the need to tackle the water crisis are important. Education and advocacy will enable all individuals to make responsible choices in water use and collectively work for sustainable water management.

In conclusion, realizing the interconnection between water, wastewater, and the well-being of human-kind and the environment will lead us toward a future where clean and accessible water is not a crisis but a human right.

Realizing also that there is a need for continuous research and development to further enhance technologies and infrastructure to treat wastewater, through innovation in this area, we can find more cost-effective and efficient solutions to treat industrial and domestic wastewater, thus putting low-pressure demands on the water resources. To continue, the water crisis requires a transition in the mind toward a circular economy approach, which is the idea that wastewater should not be treated as waste but should be treated as a valuable resource to be recycled and reused. Such things as water reclamation and reuse go a long way in completing the cycle of water management, ensuring that sustainability and resilience are maintained in the face of growing water scarcity.

However, it is key to appreciate that the solutions to these challenges regarding industrial and household wastewater are a matter of concerted effort and investment in the long run. This should take cognizance of not only financial and human resources but also political will, public engagement, and international cooperation.

In conclusion, although the problems and challenges of managing industrial and domestic sewage are enormous, they are not insurmountable. With proactive measures, collaborative partnerships, and a commitment to sustainability, we can work toward a future where clean water is abundant for all.

REFERENCES

1. Jebin Ahmed, Abhijeet Thakur, Arun Goyal. Industrial wastewater and its toxic effects. *Water, Air, & Soil Pollution*, 232(4), 189–205, 2021. doi:10.1007/s11270-021-05154-8
2. H. Kiestra, E. Eggers. Treatment of industrial wastewaters. In: *Industrial Wastewater Management Handbook*, edited by Frank Woodard, Butterworth-Heinemann, pp. 125–145, 1986. ISBN:9780409951163.
3. Elorm Obotey Ezugbe, Sudesh Rathilal. Membrane technologies in wastewater treatment: A review. *Water*, 12(5), 1166, 2020.
4. Shihao Jia. Biological treatment of industrial wastewater. *Sustainability*, 15(4), 2234, 2023.
5. J. Chenoweth, B. Durham, L. Jobs. Valeur économique de l'eau usée traitée. *Water Science and Technology*, 55(8–9), 325–332, 2007. doi:10.2166/wst.2007.325
6. Ismail Rimi Abubakar, Nuhu Dalhat Nuaza. Household attitudes toward wastewater recycling in Saudi Arabia. *Sustainability*, 14(12), 7458, 2022. doi:10.3390/su14127458
7. Hannachi Abdelhakim. Gestion et Valorisation des Eaux Usées en Algérie. *Larhyss Journal*, 19(17), 59–72, 2014.

8. Jyotsana Maura, Suchita Atriya, Anfal Archi. *The Treatment of Wastewater, Recycling and Reuse—Past, Present, and in the Future*. *Water Science and Technology*, 87(3), 543–557, 2023. doi:10.2166/wst.2023.001
9. Maria Takman, Catherine J. Paul, Åsa Davidsson, Moa Jinbäck, Stefan Blomqvist, Michael Cimbritz. MBR and GAC filtration followed by UV disinfection: Implications for wastewater reuse at full scale. *Water Research*, 200, 117032, 2024.

Wastewater Disinfection Methods and Pollutant Removal Treatment

4

Merieme Ben Ali and Sanaa Namaane

4.1 INTRODUCTION

Wastewater management is an essential aspect of urban planning and environmental management [1,2]. By effectively treating and reusing wastewater, we can protect public health, preserve natural ecosystems, and contribute to sustainable development goals. Wastewater is any water whose quality has been altered by human activity. It includes a wide range of contaminants and comes from a variety of sources, including domestic, industrial, agricultural, and commercial activities [3]. The three main types are domestic wastewater, which typically contains organic matter, pathogens, and various household chemicals; industrial wastewater, which can include a wide range of pollutants such as heavy metals, organic chemicals, and toxic substances; and finally agricultural wastewater, which often contains fertilizers, pesticides, and animal waste, contributing to nutrient pollution and microbial contamination [4,5]. For these reasons, water treatment is crucial for several reasons: it reduces the risk of disease transmission and protects the environment by preventing pollution which can harm aquatic ecosystems, decrease biodiversity, and cause issues such as algal blooms and dead zones. Moreover, modern wastewater treatment processes can recover valuable resources such as nutrients (nitrogen and phosphorus), energy (biogas from anaerobic digestion), and water for reuse, thereby supporting sustainable practices.

Wastewater, often viewed as a discarded liquid, holds the potential to serve as an alternative water source. However, this necessitates meticulous management of its collection, treatment, and disposal. Once water is contaminated by toxic compounds, it must undergo thorough treatment before it can be safely reused. This can be achieved by applying efficient and cost-effective technologies to remove pollutants. Traditional treatment methods, including screening, coagulation/flocculation, filtration, and chlorination/fluoridation, are insufficient for effectively removing high levels of pollutants such as organic carbon, nitrogen compounds, and heavy metals [6]. However, technological advancements and innovative approaches are continually enhancing the efficiency of wastewater treatment systems, addressing the increasing challenges brought about by population growth and industrialization [7].

This chapter examines various disinfection techniques, including chlorination, ultraviolet (UV) irradiation, and ozonation, all of which are essential for the elimination of pathogens and the safe discharge of water. It also covers physico-chemical and biological treatments such as coagulation/electrocoagulation, filtration, adsorption, advanced oxidation processes, and biological treatment methods.

4.2 WASTEWATER DISINFECTION METHOD

4.2.1 Chlorination

Chlorination has been used in the water industry for many decades, serving as a primary method for disinfecting water and ensuring it is safe for consumption by inactivating pathogens present in the source water. First employed in the late nineteenth century [8], this technique involves adding chlorine or chlorine compounds to water to eliminate harmful microorganisms and pathogens such as bacteria, viruses, and protozoans, which can cause diseases like cholera, dysentery, and typhoid fever [9]. Chlorination is also used for the oxidation of some organic and inorganic components in water, besides disinfection. The process of oxidation occurs to do away with tastes, odors, and colors in the water, thus enhancing the water quality [10]. A significant advantage of chlorination is its residual effect, which can reduce algal growth in sedimentation basins and filters and provide the necessary elimination in the distribution system to help prevent biological regrowth [11]. However, during the chlorination process, chlorine can react with natural organic matter present in the water, forming potentially harmful by-products. The most well-known of these by-products are trihalomethanes and haloacetic acids, which have raised significant concerns within the water treatment community. This has led authorities to review and modify chlorination practices to minimize the formation of these hazardous compounds, ensuring safer drinking water standards [12]. Studies show that using chlorine gas (Cl_2) for chlorination is more effective in ensuring water safety. However, there is often a delicate balance between maintaining high water quality and managing operational costs [12].

4.2.2 Chlorine Dioxide

Chlorine dioxide (ClO_2) is a powerful oxidizing agent used for water treatment as an alternative disinfectant to chlorine. The use of chlorine dioxide in water systems ranges from 1944 to the current day [13]. Chlorine dioxide disinfects water through a powerful oxidation process. It effectively oxidizes inorganic pollutants such as iron (I), manganese (II), and arsenic (III). Additionally, ClO_2 reacts with organic materials like phenols, tertiary amines, and anilines, breaking down complex molecules into simpler forms. This not only helps remove unwanted tastes, odors, and color from the water but also enhances overall water quality [14]. Chlorine dioxide also disrupts the cell walls of bacteria, viruses, and protozoa, effectively inactivating them. It is effective against a wide range of pathogens, including bacteria, viruses, and protozoa. It kills microorganisms even in low concentrations, making it a versatile disinfectant [15].

This method offers several advantages over traditional chlorine treatment. Chlorine dioxide significantly reduces the formation of disinfection by-products (DBP), which are potential health hazards, making it a safer and more effective alternative for water disinfection [16]. ClO_2 maintains its disinfectant properties across a broad pH range, providing consistent performance in varying water conditions. Chlorine dioxide maintains its disinfectant properties across a broad pH range and exhibits a longer-lasting residual effect. This ensures consistent performance in varying water conditions, providing ongoing protection against microbial contamination [17,18].

4.2.3 UV Disinfection

UV disinfection is a highly effective water treatment process used since 1906. This technique utilizes UV light to inactivate microorganisms by causing damage to their DNA and RNA. This damage prevents the microorganisms from reproducing, ultimately rendering them harmless and ensuring the safety of the water [19]. UV light is commonly produced using low-pressure mercury lamps, which emit in the 200–300 nm wavelength range, with the most frequently utilized wavelength being 254 nm. These lamps are integrated into specific UV reactors positioned along the water flow [20]. To properly design and operate a UV reactor, the designer must consider several operating parameters, optimizing the lamp-to wall distance and radiation dosage depending on water quality. UV dosage, that is the ratio between total incident radiation intensity (averaged on all directions and all wavelengths) and exposure time, is a fundamental parameter [21]. Several experimental and theoretical studies have been carried out to identify design concepts that lead to better radiation-hydrodynamic interaction and, ultimately, better reactor performance [22,23].

For a UV light-induced reaction to occur, the UV light must first be absorbed. Aromatic compounds are generally effective absorbers of UV light, particularly the aromatic pyrimidine heterocyclic bases found in DNA, such as cytosine and thymine, and in RNA, such as cytosine and uracil. This absorption leads to the formation of pyrimidine dimers in DNA, which can interrupt DNA replication and ultimately prevent reproduction [24]. The effectiveness of UV light disinfection and absorption is highly dependent on the UV dose in the irradiation chamber. As the dosage increases, the effects range from cell inactivation due to DNA/RNA damage to cell wall damage caused by protein absorption, leading to the death of microorganisms. The effective surface area and distribution of microbes are also critical factors, as UV inactivation varies significantly between different microbes. Consequently, the effectiveness of UV disinfection depends heavily on the type of microorganisms, their concentration, and the quality of the water [25]. UV disinfection method offers several advantages over conventional chemical disinfection techniques. It eliminates the need for chemical additives, avoids the production of toxic DBP, and prevents the development of bacterial resistance to disinfectants. Up until now, experimental and theoretical studies are ongoing to optimize UV wavelengths, develop advanced UV lamps, and improve UV reactors, aiming to make UV disinfection more effective, sustainable, and accessible for wider use [26–28]. Additionally, research is focused on integrating UV disinfection with other water treatment methods, such as ozonation and membrane filtration, to achieve more comprehensive and effective water purification [29,30].

4.2.4 Ozonation

Ozonation is a water treatment process that involves the use of ozone (O_3) to disinfect water and remove contaminants. Ozone is a powerful oxidizing agent that can effectively kill bacteria, viruses, and other microorganisms, as well as break down organic and inorganic pollutants [31]. Ozone is generated on-site using an ozone generator, which typically employs electrical discharge or UV light to convert oxygen (O_2) into ozone (O_3) [32,33]. The generated ozone is then introduced into the water through a diffuser or injector, creating fine bubbles that allow the ozone to dissolve in the water. Once in the water, ozone reacts with organic and inorganic substances, oxidizing contaminants and breaking down complex molecules into simpler, less harmful ones. The application of ozone involves two reaction mechanisms: the direct reaction, favored by the ozone itself, and the indirect reaction involving the OH radicals formed during the ozonation treatment [34]. Ozone also attacks the cell walls of microorganisms, effectively killing bacteria, viruses, and other pathogens by disrupting their cellular structure. Due to its highly reactive nature and short half-life, ozone decomposes quickly back into oxygen (O_2), leaving no harmful residues in the water. Additionally, ozonation can break down the polymer that constitutes microplastics into functional groups that contain oxygen [35,36].

Ozonation is widely used to purify drinking water, ensuring it is safe for consumption, and is also employed in wastewater treatment to remove pollutants before discharge or reuse. The ozonation method offers several benefits, including effective disinfection, as ozone is more effective than chlorine at killing

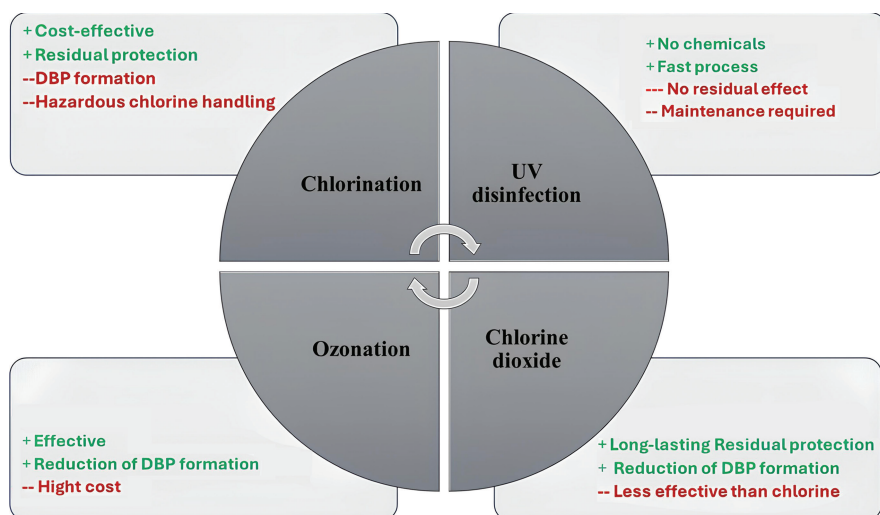


FIGURE 4.1 Advantages and disadvantages of wastewater disinfection.

bacteria, viruses, and protozoa. Additionally, ozone leaves no chemical residues, unlike chlorine. It also oxidizes a wide range of organic and inorganic contaminants, including pesticides, pharmaceuticals, and heavy metals. Furthermore, ozonation can remove unpleasant tastes and odors from water by breaking down the compounds responsible for them [37,38].

However, ozonation presents some challenges and considerations, including higher equipment and operational costs compared to other disinfection methods, and the need for careful monitoring and control to ensure the effective and safe application of ozone. Overall, ozonation is a powerful and effective method for disinfecting and purifying water, offering significant advantages while also presenting certain operational challenges. For this reason, current research is focused on developing a hybrid ozonation process that can make the process economically feasible [39,40] (Figure 4.1).

4.3 POLLUTANT REMOVAL TREATMENT

4.3.1 Physical-Chemical Treatment

Wastewater treatment uses a variety of physical and chemical methods to remove contaminants and improve water quality before it is released into the environment or reused. These methods of wastewater treatment include screening, which removes large debris, while sedimentation allows solids to settle. Flotation uses air bubbles to lift contaminants and filtration retains particles in a filter medium. Other evolving methods include adsorption, coagulation, and filtration, which will be discussed in more detail later. All these methods form an integral part of effective wastewater treatment and are often combined with biological treatments to ensure complete purification.

4.3.1.1 Coagulation/electrocoagulation

Coagulation is a crucial water treatment process that involves adding chemicals based on aluminum and iron salt to neutralize the charges of suspended particles, colloids, and dissolved organic substances so that they agglomerate into larger particles called flocs [41,42]. This is then followed by rapid mixing to

uniformly distribute the coagulants and then gentle agitation during flocculation to help the formation of larger flocs. These flocs are then removed by the sedimentation and filtration processes. Coagulation is effective in reducing turbidity and removing a wide range of contaminants, including suspended solids and pathogens, thereby improving water quality. However, it requires careful handling of the chemicals, precise dosing, and generates sludge that needs to be managed properly [43].

However, the electrochemical treatment technologies developed in recent years have several advantages, such as their versatility, the absence of added chemicals and their simplicity of use. This electrochemical process for eliminating contaminants from water and wastewater includes electrochemical oxidation, electrochemical reduction, electrocoagulation (EC) and electrocoagulation/flotation (ECF), and electrodialysis processes [44]. EC is a process used to destabilize contaminants in drinking and wastewater particularly those comprising colloids which are microscopic particles ranging in size from 1 nm to 2 μm , dispersed in a solution, making them difficult to separate from water. Due to their small size, colloids do not settle under gravity and can pass through the pores of standard filtration media, posing a challenge for conventional water treatment methods. EC effectively addresses this issue by aggregating these particles, allowing for easier removal from the water [6]. In general, coagulation occurs in a chemical reactor where suspended particles collide with counter-particles and are agglomerated by coagulating agents to form a water-insoluble complex. This operation is followed by a sedimentation process, where the aggregated particles are removed through gravity settling [45].

The EC process is a technology that combines coagulation, flotation, and electrochemistry that was first proposed in 1889 (London) [46] to treat domestic wastewater. In this process, the removal of contaminants is done through several mechanisms, including electrochemical, chemical, and physical processes. The reduction of cathodic impurities in water, followed by electro-flotation, is a key aspect of EC reactions [47]. The hydrogen or oxygen bubbles produced at the electrode assist in lifting the coagulated particles to the surface of the solution via electro-flotation (Figure 4.2). The effectiveness of EC relies on the precise control of several operational parameters. These include the distance between the electrodes, the pH of the solution, the type of electrodes used, the applied current density, and the electrode configuration [48,49].

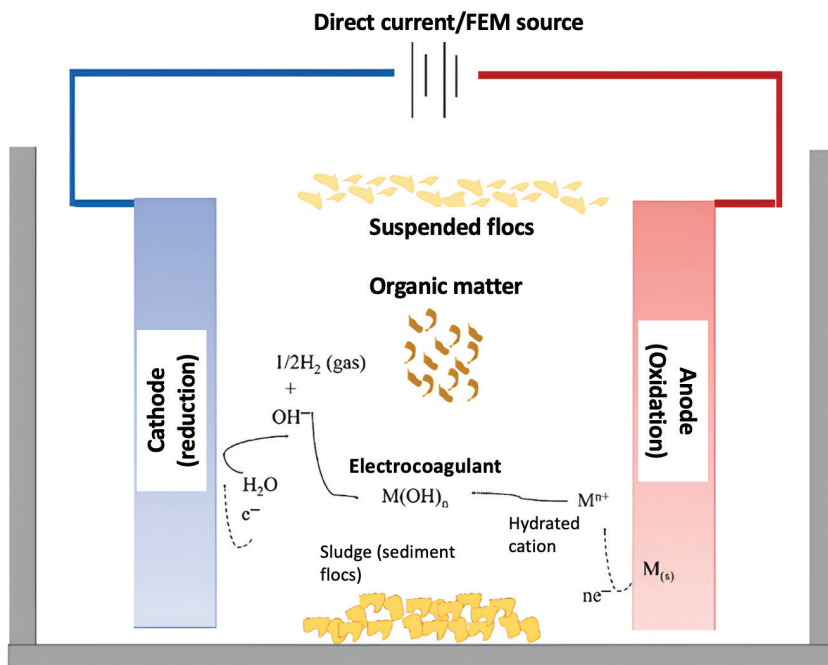


FIGURE 4.2 Simple diagram of the reactions occurring within electrocoagulation processes. (Milad Mousazadeh et al. [6], with permission from Elsevier.)

The EC process has been effectively utilized to remove various contaminants, including phosphate, chromium, iron, cobalt, copper, and cadmium [50–54]. Additionally, the EC process has successfully eliminated pharmaceutical pollutants, such as ampicillin, ampicillin hydrochloride, and amoxicillin [55,56].

4.3.1.2 Filtration

The water filtration process has long been known as a water treatment technique that involves several stages, starting with pretreatment, where large debris is removed by sieving, and coagulation and flocculation are used to form larger particles from smaller ones. This is followed by sedimentation, where these particles settle in the water. Filtration then occurs by passing water through the material to remove particulate and other impurities, using different methods such as sand filtration, activated carbon filtration, and membrane filtration (microfiltration, ultrafiltration, nanofiltration, and reverse osmosis) to remove fine particles, microorganisms, and dissolved contaminants [57,58].

Recent advancements in membrane manufacturing technology have led to various innovations, including surface modification, optimization of operating parameters, and combining technologies to enhance membrane performance [59]. Membranes are commonly used in filtration processes. This technique requires a driving force such as pressure, concentration, or electrical potential gradients to separate the desired components, with effectiveness influenced by membrane pore size. The most widely recognized filtration processes leverage pressure gradients, including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), and forward osmosis (FO) [58].

Numerous reports since 1997 have examined the use of MF membranes, which include polymeric or ceramic membranes that have the largest size of pores ranging from 50 to 500 nm. These membranes are often employed as pretreatment to enhance the efficiency of NF and RO processes [60,61]. The UF membrane is another type of membrane used for water purification with smaller pore sizes ranged between 2 and 50 nm. UF membranes can be used to separate viruses, colors, and colloidal organic substances [62]. Moreover, NF membranes are well-known for their ability to separate and remove heavy metals and salts, as well as their exceptional effectiveness in eliminating protozoa and viruses such as norovirus and rotavirus. Additionally, these membranes are highly efficient at removing pharmaceutical compounds, including amino acids, endocrine-disrupting compounds, DBP, and pharmaceuticals and personal care products (PPCPs) from liquid solution [58,63]. On the other hand, RO is a widely used water purification method that employs a semi-permeable membrane to separate and remove dissolved solids, organic compounds, pyrogens, submicron colloidal matter, color, and bacteria by applying pressure to overcome osmotic pressure. The RO system effectively separates dissolved solutes from water, allowing only water molecules to pass through the hydrophilic membrane. This technology has proven useful for treating effluents from various industries, including chemical, textile, pulp and paper, petrochemical, and food, making it an essential tool for diverse water purification needs [64–69]. These methods have led to significant advancements, resulting in the development of various membranes, including carbon membranes, carbon nanotube membranes, carbon fiber membranes, activated carbon membranes, and graphene-based membranes [70,71].

Moreover, the use of sand filters has grown significantly as researchers have identified their benefits in water treatment. The mechanism of these filters involves multiple physical, chemical, and biological processes that work together to remove contaminants from the water. The main advantage of a sand filter is its ability to remove not only suspended solids and particles but also other chemical constituents, including micropollutants, nitrogen compounds, heavy metals, pesticides, and biological contaminants such as pathogenic microorganisms and viruses. As water passes through the sand layer, larger particles and suspended solids are trapped on the surface and within the pores of the sand bed. This initial physical filtration removes debris, sediment, and particulate matter [72]. Next are the chemical processes, where the sand particles adsorb dissolved organic and inorganic substances from the water. This includes micropollutants, such as pesticides and heavy metals. Certain chemical reactions can occur within the filter bed, such as the oxidation of iron and manganese, which precipitates these metals and allows for their removal [73]. Over time, a biofilm layer, known as the *schmutzdecke*, forms on the surface of the sand which means “dirty layer” in German. This layer consists of bacteria, protozoa, and other microorganisms that consume organic matter and pathogens, thereby improving water quality. The biofilm captures and

biologically degrades harmful microorganisms, including bacteria, viruses, and protozoa. This reduces the microbial load in the filtered water [74]. There are two types of biological sand filters: the slow sand filter (SSF) [75] and the rapid sand filter (RSF). These sand biofiltration systems can be designed in various forms, including columns, vessels, rectangular or square polyethylene water tanks, or concrete tanks, depending on the treatment scale, which can range from household use to full-scale drinking water production plants. The main difference between these two systems lies in their filtration rates [76].

Numerous studies have evaluated the efficiency of sand filters; indeed, Hedegaard and Albrechtsen investigated the potential for RSFs to remove pesticides at Danish waterworks. Their study demonstrated a clear removal capability for pesticides such as bentazone, glyphosate, and p-nitrophenol. The most significant microbial removal was observed for bentazone, with its concentration in the water phase decreasing to less than 50% of the initial concentration due to microbial activity [77].

Some researchers are developing simulation models to predict their filtration performance. Schijven et al. used a pilot-scale sand filter to create a model that forecasts the removal of human pathogenic viruses and bacteria. This model is based on experimental data obtained for the elimination of bacteriophage MS2 and *E. coli*, which serve as model microorganisms for pathogenic viruses and bacteria. The model incorporates operational conditions such as temperature, the age of the *schmutzdecke* (biofilm layer), sand grain size, and filtration rate. The varying contributions of the *schmutzdecke* to the removal of MS2 and *E. coli* WR1 are attributed to their different sticking efficiencies [78].

In general, wastewater treatment by filtration faces a number of challenges, including membrane fouling and scaling, high energy consumption, and concentrate removal problems. Membranes can also degrade chemically and physically over time, requiring frequent maintenance and replacement. Efficient filtration often requires extensive pretreatment to avoid rapid fouling, which increases complexity and cost. Continuous advances in membrane technology and integrated treatment approaches are essential to meet these challenges effectively (Figure 4.3).

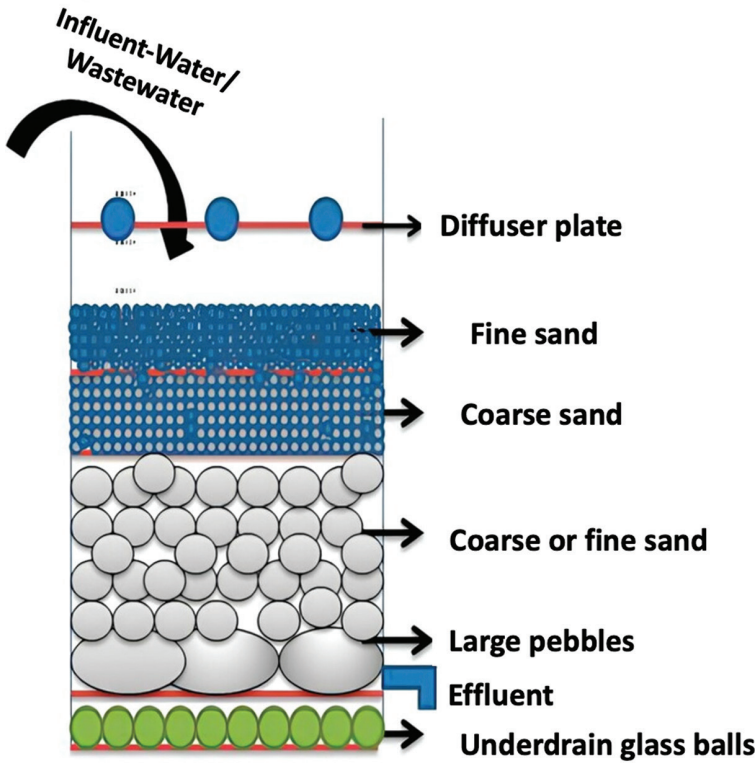


FIGURE 4.3 Schematic view of a slow sand filter column (slow sand filtration for water and wastewater treatment – a review).

4.3.1.3 Adsorption

Adsorption is a widely used process for the effective removal of contaminants from water. It involves the accumulation of pollutants from the water onto the surface of a solid material, known as the adsorbent. The adsorption occurs due to physical forces (van der Waals forces) or chemical bonding between the adsorbate and the adsorbent. The adsorption mechanism allows for distinguishing between the physical adsorption (Physisorption), which typically used for organic contaminants, is reversible and involves weak van der Waals forces without significant energy changes, and the chemical adsorption (Chemisorption) which is generally used for specific contaminants like heavy metals and involves the formation of chemical bonds between adsorbent and adsorbate [79]. The adsorption is particularly effective for removing a variety of organic and inorganic contaminants using several different categories of adsorbents such as activated carbon, zeolites, silica gel, and various synthetic resins [80]. The efficiency of this process is influenced by numerous factors, including the surface area and porosity of the adsorbent, with higher surface area and porosity resulting in more efficient adsorption [81]. Contaminant concentration also plays a role, with higher concentration gradients increasing adsorption rates. The pH of the solution has an impact on the ionization state of the adsorbate and the surface charge of the adsorbent, which influences adsorption efficiency. Temperature is another factor, with low temperatures generally favoring physical adsorption, whereas chemisorption can be endothermic. Finally, contact time is important, a longer contact time generally results in greater adsorption until equilibrium is reached [82].

Adsorption is a versatile and efficient method for removing a wide range of contaminants from water with ongoing advancements in adsorbent materials and technologies enhancing its effectiveness and applicability across various water treatment scenarios. The study by Burakov et al. demonstrates that nanotechnology-based materials, including carbon nanotubes, graphene, and graphene-based substances, which possess unique physical, chemical, and mechanical properties, show great potential as a promising alternative to traditional adsorbents for the more effective removal of heavy metal pollutants from wastewater effluents [83]. Other research has focused on the effectiveness of magnetic adsorbents. Notably, Ahmed et al. investigated the use of a bentonite@MnFe₂O₄ clay composite as an adsorbent for Cr(III) and Cr(VI) ions in aqueous solutions. Their results revealed impressive removal efficiencies of 97.37% for Cr(III) and 98.65% for Cr(VI) using this composite material [84].

4.3.1.4 Advanced oxidation processes

The advanced oxidation processes (AOPs) are widely used in the treatment of water and industrial effluents to eliminate persistent organic pollutants and hazardous substances. They are a promising approach to improving water and wastewater treatment. They have emerged as promising alternative disinfection methods that are environmentally friendly and effective compared with conventional methods.

AOPs are redox technologies comprising different processes such as ozonation, ozonation coupled with hydrogen peroxide (H₂O₂) and UV radiation, the Fenton reaction, photocatalysis activated by semiconductors, electrochemical oxidation, and a variety of combinations of these processes. They are based on the in-situ formation of chemical oxidants to disinfect water and degrade various harmful organic contaminants. It is based on the production of highly reactive oxygen species distinguished by non-selectivity on the target [85,86].

Recent applications of AOPs have demonstrated their potential to eliminate complex chemicals, heavy metals, and color from wastewater [87]. The most extensively researched are sunlight-induced AOP, which utilizes semiconductors in conjunction with other treatment techniques such as filtration, coagulation/flocculation, and carbon-based adsorption processes. This combination has led to more effective treatment of industrial wastewater. Numerous studies have underscored the effectiveness of these processes in efficiently treating highly concentrated wastewater containing multiple dyes [88].

Li et al. reported in their literature review that metallurgical slag catalysts can be used in AOP processes, enabling solid waste to be recovered and significantly improving environmental benefits [89]. Also, encapsulated transition metal nanoparticle catalysts are increasingly used in alternative environmental

pollution control processes and offer excellent performance due to their unique properties and advantages, such as the strong interaction between the transition metal core and the carbon shells, which promotes electron transfer and enhances catalytic activity [90,91].

Research has demonstrated that combining AOPs with other treatment methods creates a synergistic effect, leading to superior performance compared to individual processes. For instance, integrating AOP with biotechnology treatments has proven effective not only for pollutant degradation but also for producing value-added products with various applications [86]. Further investigations have focused on applying this approach in the textile industry, which is heavily polluted by dyes, reagents, and toxic, carcinogenic by-products. Paździor et al. reported that treating dye wastewater with an integrated membrane bioreactor system, using ozone-based AOP and photocatalysis with alginate beads as pretreatment, achieved significant decolorization and substantial reductions in both biochemical oxygen demand and chemical oxygen demand compared to single treatment methods [92].

Moreover, the combination of UV treatment with AOPs shows great promise. This technique utilizes UV radiation to initiate the photolysis of hydrogen peroxide or ozone, resulting in the formation of highly reactive hydroxyl radicals that attack and break down the chemical bonds of micropollutants, producing less harmful compounds [93]. The degradation of micropollutants in water via UV-based AOP is strongly influenced by the water matrix. In this context, various studies are focused on developing predictive methods for micropollutant degradation by combining model simulations with portable measurements [94]. In general, AOPs are extensively used in water treatment and industrial effluent management to eliminate persistent organic pollutants and hazardous substances. Despite their high efficiency and versatility, the cost and potential formation of intermediate by-products present challenges that require careful consideration and management.

4.3.2 Biological Treatment

Since the early 1900s, biological processes have been widely used to treat wastewater, using microorganisms, primarily bacteria, as biocatalysts for the biochemical oxidation and degradation of contaminants in polluted water [95]. This process is an integral part of wastewater treatment plants, which are designed to mimic and accelerate natural biodegradation processes, resulting in biologically stable water and helping to prevent the growth of microorganisms in the water distribution system; however, its global implementation remains limited. In recent years, some developed countries have adopted biological treatment for drinking water to improve cleanliness and safety [76,96].

Biological treatment processes can be broadly divided into aerobic treatment, where microorganisms break down organic matter in the presence of oxygen, and anaerobic treatment, where microorganisms break down organic matter in the absence of oxygen, producing methane and carbon dioxide as by-products. Common biological treatment methods include the activated sludge process, in which wastewater is mixed with a concentrated suspension of microorganisms (activated sludge) in an aeration tank, and oxygen is added through diffusers or mechanical aerators to promote microbial growth and degradation of organic pollutants [97,98]. There are also trickling filters, which use a bed of porous material such as stones covered with a microbial biofilm to break down organic pollutants; bio-towers, which are similar to trickling filters but taller and often filled with synthetic media to provide a large surface area for microbial growth; and membrane bioreactors, which combine a biological treatment process with membrane filtration. Microorganisms break down pollutants in a bioreactor and the treated water is separated by membranes to provide high-quality effluent. On the flip side, anaerobic digesters and up-flow anaerobic sludge bed reactors where microorganisms break down organic matter, producing biogas (methane/carbon dioxide), which can be captured and used as a source of energy [99,100]. The up-flow anaerobic sludge bed reactors offer a number of advantages, including reduced sludge production, energy recovery, and low total cost of ownership [101]. The structure that is most commonly used in biological treatment is shown in Figure 4.4.

The role of ultrasound in improving biological treatment processes has been studied by several researchers [102,103]. In fact, ultrasound can affect substances through mechanical effects, thermal

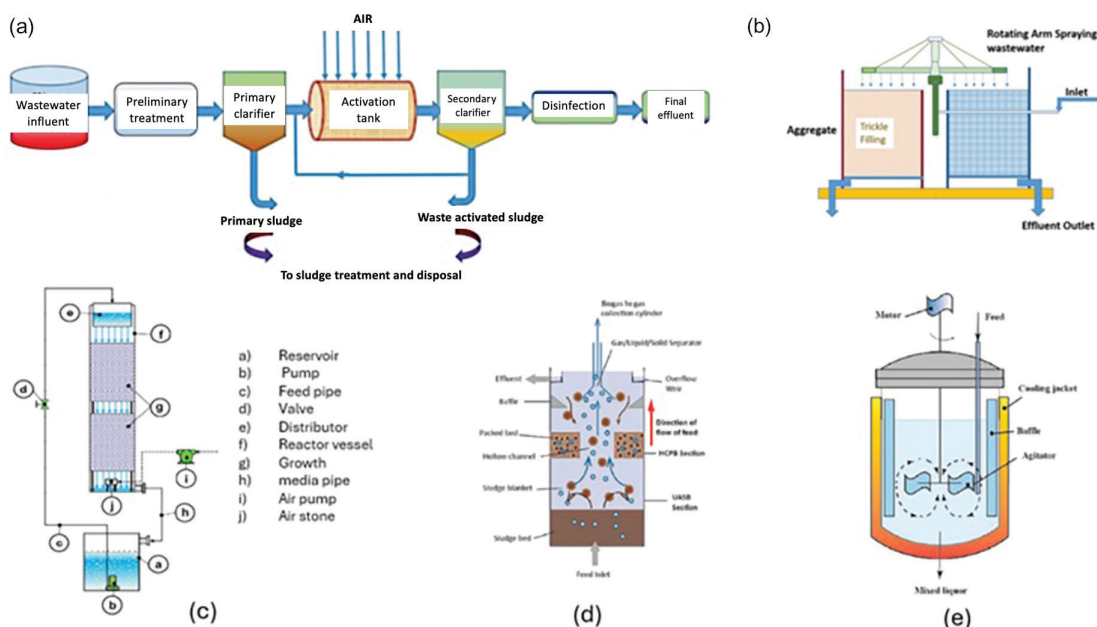


FIGURE 4.4 (a) An activated sludge system, (b) a detailed diagram of a trickling filter (review of biological treatment solutions and role of nanoparticles in the treatment of wastewater generated by diverse industries), (c) laboratory biotower (biotower application for wastewater treatment), (d) up-flow anaerobic sludge reactor, and (e) continuous anaerobic stirred-tank reactor (membrane bioreactor for wastewater treatment: a review).

effects, and cavitation effects, as reported by El Jery et al. [104]. In addition, a number of researchers have explored new ways to improve existing biological treatments, such as investigating the environmental and economic performance of emerging sludge treatments [105]. Despite the challenges of cost and by-product management, biological treatment remains a cornerstone of sustainable wastewater management, contributing to environmental protection and resource conservation.

4.4 CONCLUSION

Water is essential for life and is required for many human activities, from daily domestic use to industrial processes, all of which generate wastewater either directly or indirectly. As a result, wastewater will always be present on the planet. While traditional approaches form the basis of wastewater treatment, no single treatment method alone can ensure that water meets standards for disposal or reuse. The optimal combination of treatments will be one that is environmentally friendly and cost-effective for industry.

This chapter focuses on understanding wastewater disinfection techniques, including chlorination, which uses chlorine or chlorine compounds to kill bacteria and viruses; UV irradiation, which breaks down the DNA of microorganisms, rendering them inactive; and ozonation, which introduces ozone to oxidize and destroy pathogens. Each method is essential to eliminate pathogens and ensure that the treated water is safe for discharge or reuse. The choice of disinfection method depends on factors such as wastewater quality, regulatory requirements, and operational considerations.

In addition, this chapter discusses physico-chemical and biological pollutant removal treatments, which typically include primary treatment to remove large solids by screening and sedimentation, followed by secondary treatment using biological processes such as activated sludge, trickling filters, or membrane bioreactors to break down organic matter, and finally tertiary treatment, which may include advanced

processes such as filtration, activated carbon adsorption, and nutrient removal to target specific pollutants. Each stage is essential to effectively reduce pollutant loads and protect public health and the environment.

However, water disinfection faces a number of challenges that must be overcome to ensure safe and effective treatment. Indeed, the formation of DBP, such as those produced by chlorine, is one such challenge. Variability in water quality, including suspended solids and organic matter, can affect the effectiveness of disinfection. In general, compliance with regulatory standards requires continuous monitoring and adjustment, which increases resource requirements. In addition, it is essential to ensure effective water treatment, which underlines the need for continued research, innovation and investment in disinfection, and wastewater treatment technologies.

REFERENCES

1. L. Lambiasi, D. Ddiba, K. Andersson, M. Parvage, and S. Dickin, "Greenhouse gas emissions from sanitation and wastewater management systems: A review," *J. Water Clim. Chang.*, vol. 15, no. 4, pp. 1797–1819, 2024, doi:10.2166/wcc.2024.603.
2. UNESCO, "L'Eau pour la prospérité et la paix," pp. 1–1, 2024, <https://www.unesco.org/reports/wwdr/fr/2024?hub=68313>.
3. Z. Su, L. Chen, and D. Wen, "Impact of wastewater treatment plant effluent discharge on the antibiotic resistome in downstream aquatic environments: A mini review," *Front. Environ. Sci. Eng.*, vol. 18, no. 3, pp. 1–11, 2024, doi:10.1007/s11783-024-1796-3.
4. Y. Pérez, E. Vargas, D. García-Cortés, W. Hernández, H. Checo, and U. Jáuregui-Haza, "Efficiency and effectiveness of systems for the treatment of domestic wastewater based on subsurface flow constructed wetlands in Jarabacoa, Dominican Republic," *Water Sci. Eng.*, vol. 17, no. 2, pp. 118–128, 2024, doi:10.1016/j.wse.2023.08.004.
5. N. O. Solomon, S. Kanchan, and M. Keshari, "Nanoparticles as detoxifiers for industrial wastewater," *Water. Air. Soil Pollut.*, vol. 235, no. 3, pp. 1–26, 2024, doi:10.1007/s11270-024-07016-5.
6. M. Mousazadeh et al., "A systematic diagnosis of state of the art in the use of electrocoagulation as a sustainable technology for pollutant treatment: An updated review," *Sustain. Energy Technol. Assessm.*, vol. 47, 2021, doi:10.1016/j.seta.2021.101353.
7. L. Liu, G. Hall, and P. Champagne, "Disinfection processes and mechanisms in wastewater stabilization ponds: A review," *Environ. Rev.*, vol. 26, no. 4, pp. 417–429, 2018, doi:10.1139/er-2018-0006.
8. US Environmental Protection Agency, "The history of drinking water treatment," *Public Health*, vol. 40, no. 4606, pp. 1–4, 2000.
9. M. Mohseni, E. A. McBean, and M. J. Rodriguez, "Chlorination of drinking water: Scientific evidence and policy implications," *Glob. Issues Water Policy*, vol. 17, pp. 357–373, 2017, doi:10.1007/978-3-319-42806-2_19.
10. Djamel Ghernaout, "Water treatment chlorination : An updated mechanistic insight review," *Chem. Res. J.*, vol. 4, no. 2, pp. 125–138, 2018.
11. Q. Shen, J. Zhu, L. Cheng, J. Zhang, Z. Zhang, and X. Xu, "Enhanced algae removal by drinking water treatment of chlorination coupled with coagulation," *Desalination*, vol. 271, no. 1–3, pp. 236–240, 2011, doi:10.1016/j.desal.2010.12.039.
12. D. Stefán, N. Erdélyi, B. Izsák, G. Záray, and M. Vargha, "Formation of chlorination by-products in drinking water treatment plants using breakpoint chlorination," *Microchem. J.*, vol. 149, no. June, p. 104008, 2019, doi:10.1016/j.microc.2019.104008.
13. M. L. Granstrom and G. Fred Lee, "Generation and use of chlorine dioxide in water treatment," *JSTOR*, vol. 50, no. 11, pp. 1453–1466, 1958.
14. W. Gan, Y. Ge, Y. Zhong, and X. Yang, "The reactions of chlorine dioxide with inorganic and organic compounds in water treatment: Kinetics and mechanisms," *Environ. Sci. Water Res. Technol.*, vol. 6, no. 9, pp. 2287–2312, 2020, doi:10.1039/d0ew00231c.
15. U. H. N. M. Jefri et al., "A systematic review on chlorine dioxide as a disinfectant," *J. Med. Life*, vol. 2022, no. 3, pp. 313–318, 2022, doi:10.25122/jml-2021-0180.
16. K. Hassenberg, U. Praeger, and W. B. Herppich, "Effect of chlorine dioxide treatment on human pathogens on iceberg lettuce," *Foods*, vol. 10, no. 3, 2021, doi:10.3390/foods10030574.

17. Z. Hoko, T. N. Toto, C. F. Mapenzauswa, T. Nhiwatiwa, L. Chipfunde, and S. Hunguru, "Investigating use of chlorine dioxide for pre-treatment of raw water from polluted sources at Morton Jaffray water treatment works, Harare, Zimbabwe," *Water Pract. Technol.*, vol. 16, no. 4, pp. 1290–1306, 2021, doi:10.2166/wpt.2021.077.
18. G. Gordon and A. A. Rosenblatt, "Chlorine dioxide: The current state of the art," *Ozone Sci. Eng.*, vol. 27, no. 3, pp. 203–207, 2005, doi:10.1080/01919510590945741.
19. M. Al-Abri et al., "Chlorination disadvantages and alternative routes for biofouling control in reverse osmosis desalination," *NPJ Clean Water*, vol. 2, no. 1, 2019, doi:10.1038/s41545-018-0024-8.
20. A. Qadri and M. Alam, "Drinking water treatment using advanced oxidation processes," *Int. J. Chem. Biochem. Sci.*, vol. 25, no. 14, pp. 154–163, 2024. <https://www.iscientific.org/wp-content/uploads/2024/03/19-IJCBS-24-25-14-19.pdf>.
21. K. Song, M. Mohseni, and F. Taghipour, "Application of ultraviolet light-emitting diodes (UV-LEDs) for water disinfection: A review," *Water Res.*, vol. 94, pp. 341–349, 2016, doi:10.1016/j.watres.2016.03.003.
22. A. M. Zyara, E. Torvinen, A. M. Veijalainen, and H. Heinonen-Tanski, "The effect of UV and combined chlorine/UV treatment on coliphages in drinking water disinfection," *Water (Switzerland)*, vol. 8, no. 4, 2016, doi:10.3390/w8040130.
23. D. A. Sozzi and F. Taghipour, "UV reactor performance modeling by Eulerian and Lagrangian methods," *Environ. Sci. Technol.*, vol. 40, no. 5, pp. 1609–1615, 2006, doi:10.1021/es051006x.
24. J. Gibson, J. Drake, and B. Karney, "UV disinfection of wastewater and combined sewer overflows," *Adv. Exp. Med. Biol.*, vol. 996, pp. 267–275, 2017, doi:10.1007/978-3-319-56017-5_22.
25. A. Hassen, M. Mahrouk, H. Ouzari, M. Cherif, A. Boudabous, and J. J. Damelincourt, "UV disinfection of treated wastewater in a large-scale pilot plant and inactivation of selected bacteria in a laboratory UV device," *Bioresour. Technol.*, vol. 74, no. 2, pp. 141–150, 2000, doi:10.1016/S0960-8524(99)00179-0.
26. S. Kang et al., "Design optimization of a cylindrical UV-C LED reactor for effective water disinfection with numerical simulations and test reactor fabrication," *J. Environ. Chem. Eng.*, vol. 12, no. 2, p. 112366, 2024, doi:10.1016/j.jece.2024.112366.
27. K. Meiramkulova et al., "Calcination-modified zeolite filtration and UV disinfection for contaminant Mitigation in groundwater," *Case Stud. Chem. Environ. Eng.*, vol. 10, no. April, p. 100781, 2024, doi:10.1016/j.csee.2024.100781.
28. W. Sun et al., "Ultraviolet technology application in urban water supply and wastewater treatment in China: Issues, challenges and future directions," *Water Res.* vol. 23, no. April, p. 100225, 2024, doi:10.1016/j.wroa.2024.100225.
29. L. Farkas et al., "Comparison of the effectiveness of UV, UV/VUV photolysis, ozonation, and ozone/UV processes for the removal of sulfonamide antibiotics," *J. Environ. Chem. Eng.*, vol. 12, no. 1, 2024, doi:10.1016/j.jece.2023.111845.
30. G. B. Dirisu, U. C. Okonkwo, I. P. Okokpujie, and O. S. I. Fayomi, "Comparative analysis of the effectiveness of reverse osmosis and ultraviolet radiation of water treatment," *J. Ecol. Eng.*, vol. 20, no. 1, pp. 61–75, 2019, doi:10.12911/22998993/93978.
31. J. Wang and H. Chen, "Catalytic ozonation for water and wastewater treatment: Recent advances and perspectives," *Sci. Total Environ.*, vol. 704, p. 135249, 2020, doi:10.1016/j.scitotenv.2019.135249.
32. H. Claus, "Ozone generation by ultraviolet lamps," *Photochem. Photobiol.*, vol. 97, no. 3, pp. 471–476, 2021, doi:10.1111/php.13391.
33. M. Rodríguez-Peña, J. A. Barrios Pérez, J. Llanos, C. Sáez, M. A. Rodrigo, and C. E. Barrera-Díaz, "New insights about the electrochemical production of ozone," *Curr. Opin. Electrochem.*, vol. 27, p. 100697, 2021, doi:10.1016/j.coelec.2021.100697.
34. M. Mainardis, M. Buttazzoni, N. De Bortoli, M. Mion, and D. Goi, "Evaluation of ozonation applicability to pulp and paper streams for a sustainable wastewater treatment," *J. Clean. Prod.*, vol. 258, p. 120781, 2020, doi:10.1016/j.jclepro.2020.120781.
35. X. T. Bui, T. D. H. Vo, P. T. Nguyen, V. T. Nguyen, T. S. Dao, and P. D. Nguyen, "Microplastics pollution in wastewater: Characteristics, occurrence and removal technologies," *Environ. Technol. Innov.*, vol. 19, p. 101013, 2020, doi:10.1016/j.eti.2020.101013.
36. S. Ziembowicz and M. Kida, "The effect of water ozonation in the presence of microplastics on water quality and microplastics degradation," *Sci. Total Environ.*, vol. 929, no. April, 2024, doi:10.1016/j.scitotenv.2024.172595.
37. A. C. Mecha and M. N. Chollom, "Photocatalytic ozonation of wastewater: A review," *Environ. Chem. Lett.*, vol. 18, no. 5, pp. 1491–1507, 2020, doi:10.1007/s10311-020-01020-x.
38. S. Lim, J. L. Shi, U. von Gunten, and D. L. McCurry, "Ozonation of organic compounds in water and wastewater: A critical review," *Water Res.*, vol. 213, no. September 2021, p. 118053, 2022, doi:10.1016/j.watres.2022.118053.
39. S. N. Malik, P. C. Ghosh, A. N. Vaidya, and S. N. Mudliar, "Hybrid ozonation process for industrial wastewater treatment: Principles and applications: A review," *J. Water Process Eng.*, vol. 35, no. February, 2020, doi:10.1016/j.jwpe.2020.101193.

40. G. A. Jamali et al., "Holistic insight mechanism of ozone-based oxidation process for wastewater treatment," *Chemosphere*, vol. 359, no. May, p. 142303, 2024, doi:10.1016/j.chemosphere.2024.142303.
41. G. U. Semblante, J. Z. Lee, L. Y. Lee, S. L. Ong, and H. Y. Ng, "Brine pre-treatment technologies for zero liquid discharge systems," *Desalination*, vol. 441, no. April, pp. 96–111, 2018, doi:10.1016/j.desal.2018.04.006.
42. C. Zhao et al., "Application of coagulation/flocculation in oily wastewater treatment: A review," *Sci. Total Environ.*, vol. 765, p. 142795, 2021, doi:10.1016/j.scitotenv.2020.142795.
43. V. Saritha, N. Srinivas, and N. V. Srikanth Vuppala, "Analysis and optimization of coagulation and flocculation process," *Appl. Water Sci.*, vol. 7, no. 1, pp. 451–460, 2017, doi:10.1007/s13201-014-0262-y.
44. M. Bajpai, S. S. Katoch, A. Kadier, and A. Singh, "A review on electrocoagulation process for the removal of emerging contaminants: Theory, fundamentals, and applications," *Environ. Sci. Pollut. Res.*, vol. 29, no. 11, pp. 15252–15281, 2022, doi:10.1007/s11356-021-18348-8.
45. A. H. Amran, N. S. Zaidi, K. Muda, and L. W. Loan, "Effectiveness of natural coagulant in coagulation process: A review," *Int. J. Eng. Technol.*, vol. 7, no. 3, pp. 34–37, 2018, doi:10.14419/ijet.v7i3.9.15269.
46. N. Yasri, J. Hu, M. G. Kibria, and E. P. L. Roberts, "Electrocoagulation separation processes," *ACS Symp. Ser.*, vol. 1348, pp. 167–203, 2020, doi:10.1021/bk-2020-1348.ch006.
47. P. P. Das, M. Sharma, and M. K. Purkait, "Recent progress on electrocoagulation process for wastewater treatment: A review," *Sep. Purif. Technol.*, vol. 292, p. 121058, 2022, doi:10.1016/j.seppur.2022.121058.
48. J. N. Hakizimana et al., "Electrocoagulation process in water treatment: A review of electrocoagulation modeling approaches," *Desalination*, vol. 404, pp. 1–21, 2017, doi:10.1016/j.desal.2016.10.011.
49. D. Ghernaout, "Electrocoagulation process: A mechanistic review at the dawn of its modeling," *J. Environ. Sci. Allied Res.*, vol. 2, no. 1, pp. 22–38, 2019, doi:10.29199/2637-7063/esar-201019.
50. P. I. Omwene and M. Koby, "Treatment of domestic wastewater phosphate by electrocoagulation using Fe and Al electrodes: A comparative study," *Process Saf. Environ. Prot.*, vol. 116, pp. 34–51, 2018, doi:10.1016/j.psep.2018.01.005.
51. S. Vasudevan, J. Lakshmi, and G. Sozhan, "Simultaneous removal of Co, Cu, and Cr from water by electrocoagulation," *Toxicol. Environ. Chem.*, vol. 94, no. 10, pp. 1930–1940, 2012, doi:10.1080/02772248.2012.742898.
52. R. Kamaraj and S. Vasudevan, "Evaluation of electrocoagulation process for the removal of strontium and cesium from aqueous solution," *Chem. Eng. Res. Des.*, vol. 93, no. April, pp. 522–530, 2015, doi:10.1016/j.cherd.2014.03.021.
53. L. Xu et al., "Simultaneous removal of cadmium, zinc and manganese using electrocoagulation: Influence of operating parameters and electrolyte nature," *J. Environ. Manage.*, vol. 204, pp. 394–403, 2017, doi:10.1016/j.jenvman.2017.09.020.
54. A. A. Al-Raad and M. M. Hanafiah, "Removal of inorganic pollutants using electrocoagulation technology: A review of emerging applications and mechanisms," *J. Environ. Manage.*, vol. 300, no. August, p. 113696, 2021, doi:10.1016/j.jenvman.2021.113696.
55. H. Zhang, J. Bian, C. Yang, Z. Hu, F. Liu, and C. Zhang, "Removal of tetracycline from livestock wastewater by positive single pulse current electrocoagulation: Mechanism, toxicity assessment and cost evaluation," *Sci. Total Environ.*, vol. 810, p. 151955, 2022, doi:10.1016/j.scitotenv.2021.151955.
56. G. Yoshida, N. Takeda, Y. Kitazono, K. Toyoda, K. Umetsu, and I. Ihara, "Removal of tetracycline antibiotics from dairy farm wastewater by electrocoagulation using iron electrodes," *J. Water Environ. Technol.*, vol. 18, no. 3, pp. 157–165, 2020, doi:10.2965/jwet.19-124.
57. A. Yakub et al., "Treatment of sand filter backwash water from water treatment plant," *Int. J. Adv. Sci. Technol.*, vol. 29, no. 7, pp. 12130–12137, 2020, <https://www.researchgate.net/publication/350630507>.
58. U. Chadha et al., "A review of the function of using carbon nanomaterials in membrane filtration for contaminant removal from wastewater," *Mater. Res. Express*, vol. 9, no. 1, 2022, doi:10.1088/2053-1591/ac48b8.
59. J. Cevallos-Mendoza, C. G. Amorim, J. M. Rodríguez-Díaz, and M. C. B. S. M. da Montenegro, "Removal of contaminants from water by membrane filtration: A review," *Membranes (Basel)*, vol. 12, no. 6, pp. 1–23, 2022, doi:10.3390/membranes12060570.
60. M. Rezakazemi, A. Khajeh, and M. Mesbah, "Membrane filtration of wastewater from gas and oil production," *Environ. Chem. Lett.*, vol. 16, no. 2, pp. 367–388, 2018, doi:10.1007/s10311-017-0693-4.
61. J. Mueller, Y. Cen, and R. H. Davis, "Crossflow microfiltration of oily water," *J. Memb. Sci.*, vol. 129, no. 2, pp. 221–235, 1997, doi:10.1016/S0376-7388(96)00344-4.
62. U. W. R. Siagian et al., "High-performance ultrafiltration membrane: Recent progress and its application for wastewater treatment," *Curr. Pollut. Reports*, vol. 7, no. 4, pp. 448–462, 2021, doi:10.1007/s40726-021-00204-5.
63. D. Yadav, S. Karki, and P. G. Ingole, "Current advances and opportunities in the development of nanofiltration (NF) membranes in the area of wastewater treatment, water desalination, biotechnological and pharmaceutical applications," *J. Environ. Chem. Eng.*, vol. 10, no. 4, p. 108109, 2022, doi:10.1016/j.jece.2022.108109.

64. I. G. Werten and Khoiruddin, "Reverse osmosis applications: Prospect and challenges," *Desalination*, vol. 391, pp. 112–125, 2016, doi:10.1016/j.desal.2015.12.011.
65. R. M. Garud, S. V. Kore, V. S. Kore, and G. S. Kulkarni, "A short review on process and applications of reverse osmosis," *Univers. J. Environ. Res. Technol.*, vol. 1, no. 3, pp. 233–238, 2011.
66. A. Bódalo-Santoyo, J. L. Gómez-Carrasco, E. Gómez-Gómez, F. Máximo-Martín, and A. M. Hidalgo-Montesinos, "Application of reverse osmosis to reduce pollutants present in industrial wastewater," *Desalination*, vol. 155, no. 2, pp. 101–108, 2003, doi:10.1016/S0011-9164(03)00287-X.
67. S. Vinardell, S. Astals, J. Mata-Alvarez, and J. Dosta, "Techno-economic analysis of combining forward osmosis-reverse osmosis and anaerobic membrane bioreactor technologies for municipal wastewater treatment and water production," *Bioresour. Technol.*, vol. 297, no. November 2019, p. 122395, 2020, doi:10.1016/j.biortech.2019.122395.
68. S. Ebrahimzadeh, B. Wols, A. Azzellino, B. J. Martijn, and J. P. van der Hoek, "Quantification and modelling of organic micropollutant removal by reverse osmosis (RO) drinking water treatment," *J. Water Process Eng.*, vol. 42, no. March, 2021, doi:10.1016/j.jwpe.2021.102164.
69. D. Patel, A. Mudgal, V. Patel, and J. Patel, "Water desalination and wastewater reuse using integrated reverse osmosis and forward osmosis system," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1146, no. 1, p. 012029, 2021, doi:10.1088/1757-899x/1146/1/012029.
70. M. Sajid, M. Asif, N. Baig, M. Kabeer, I. Ihsanullah, and A. W. Mohammad, "Carbon nanotubes-based adsorbents: Properties, functionalization, interaction mechanisms, and applications in water purification," *J. Water Process Eng.*, vol. 47, no. March, p. 102815, 2022, doi:10.1016/j.jwpe.2022.102815.
71. C. Li et al., "Carbon-based membrane materials and applications in water and wastewater treatment: A review," *Environ. Chem. Lett.*, vol. 19, no. 2, pp. 1457–1475, 2021, doi:10.1007/s10311-020-01112-8.
72. E. Sembiring, M. Fajar, and M. Handajani, "Performance of rapid sand filter: Single media to remove microplastics," *Water Supply*, vol. 21, no. 5, pp. 2273–2284, 2021, doi:10.2166/ws.2021.060.
73. S. Verma, A. Daverey, and A. Sharma, "Slow sand filtration for water and wastewater treatment: A review," *Environ. Technol. Rev.*, vol. 6, no. 1, pp. 47–58, 2017, doi:10.1080/21622515.2016.1278278.
74. P. Ranjan and M. Prem, "Schmutzdecke: A filtration layer of slow sand filter," *Int. J. Curr. Microbiol. Appl. Sci.*, vol. 7, no. 07, pp. 637–645, 2018, doi:10.20546/ijcmas.2018.707.077.
75. E. Guchi, "Review on slow sand filtration in removing microbial contamination and particles from drinking water," *Am. J. Food Nutr.*, vol. 3, no. 2, pp. 47–55, 2015, doi:10.12691/ajfn-3-2-3.
76. H. Abu Hasan, M. H. Muhammad, and N. I. Ismail, "A review of biological drinking water treatment technologies for contaminants removal from polluted water resources," *J. Water Process Eng.*, vol. 33, no. November 2019, p. 101035, 2020, doi:10.1016/j.jwpe.2019.101035.
77. M. J. Hedegaard and H. J. Albrechtsen, "Microbial pesticide removal in rapid sand filters for drinking water treatment - potential and kinetics," *Water Res.*, vol. 48, no. 1, pp. 71–81, 2014, doi:10.1016/j.watres.2013.09.024.
78. J. F. Schijven et al., "A mathematical model for removal of human pathogenic viruses and bacteria by slow sand filtration under variable operational conditions," *Water Res.*, vol. 47, no. 7, pp. 2592–2602, 2013, doi:10.1016/j.watres.2013.02.027.
79. S. De Gisi, G. Lofrano, M. Grassi, and M. Notarnicola, "Characteristics and adsorption capacities of low-cost sorbents for wastewater treatment: A review," *Sustain. Mater. Technol.*, vol. 9, pp. 10–40, 2016, doi:10.1016/j.susmat.2016.06.002.
80. Z. Aksu, "Application of biosorption for the removal of organic pollutants: A review," *Process Biochem.*, vol. 40, no. 3–4, pp. 997–1026, 2005, doi:10.1016/j.procbio.2004.04.008.
81. S. F. Ahmed et al., "Recent developments in physical, biological, chemical, and hybrid treatment techniques for removing emerging contaminants from wastewater," *J. Hazard. Mater.*, vol. 416, no. March, p. 125912, 2021, doi:10.1016/j.jhazmat.2021.125912.
82. B. S. Rath and P. S. Kumar, "Application of adsorption process for effective removal of emerging contaminants from water and wastewater," *Environ. Pollut.*, vol. 280, p. 116995, 2021, doi:10.1016/j.envpol.2021.116995.
83. A. E. Burakov et al., "Adsorption of heavy metals on conventional and nanostructured materials for wastewater treatment purposes: A review," *Ecotoxicol. Environ. Saf.*, vol. 148, no. November 2017, pp. 702–712, 2018, doi:10.1016/j.ecoenv.2017.11.034.
84. A. Ahmadi, R. Foroutan, H. Esmaeili, and S. Tamjidi, "The role of bentonite clay and bentonite clay@MnFe₂O₄ composite and their physico-chemical properties on the removal of Cr(III) and Cr(VI) from aqueous media," *Environ. Sci. Pollut. Res.*, vol. 27, no. 12, pp. 14044–14057, 2020, doi:10.1007/s11356-020-07756-x.
85. P. Kokkinos, D. Venieri, and D. Mantzavinos, "Advanced oxidation processes for water and wastewater viral disinfection. a systematic review," *Food Environ. Virol.*, vol. 13, no. 3, pp. 283–302, 2021, doi:10.1007/s12560-021-09481-1.

86. A. Babu Ponnusami et al., “Advanced oxidation process (AOP) combined biological process for wastewater treatment: A review on advancements, feasibility and practicability of combined techniques,” *Environ. Res.*, vol. 237, no. P1, p. 116944, 2023, doi:10.1016/j.envres.2023.116944.
87. S. Feijoo, X. Yu, M. Kamali, L. Appels, and R. Dewil, “Generation of oxidative radicals by advanced oxidation processes (AOPs) in wastewater treatment: A mechanistic, environmental and economic review,” vol. 22, no. 1. 2023, doi:10.1007/s1157-023-09645-4.
88. P. S. Chauhan, K. Singh, A. Choudhary, U. Brighu, S. K. Singh, and S. Bhattacharya, “Combined advanced oxidation dye-wastewater treatment plant: Design and development with data-driven predictive performance modeling,” *NPJ Clean Water*, vol. 7, no. 1, pp. 1–17, 2024, doi:10.1038/s41545-024-00308-7.
89. X. Li, H. Liu, Y. Zhang, J. Mahlknecht, and C. Wang, “A review of metallurgical slags as catalysts in advanced oxidation processes for removal of refractory organic pollutants in wastewater,” *J. Environ. Manage.*, vol. 352, no. December 2023, p. 120051, 2024, doi:10.1016/j.jenvman.2024.120051.
90. S. Li et al., “High-efficiency degradation of carbamazepine by the synergistic electro-activation and bimetal (FeCo@NC) catalytic-activation of peroxymonosulfate,” *Appl. Catal. B Environ.*, vol. 338, no. July, p. 123064, 2023, doi:10.1016/j.apcatb.2023.123064.
91. T. Yu et al., “Recent advances in the applications of encapsulated transition-metal nanoparticles in advanced oxidation processes for degradation of organic pollutants : A critical review,” *Appl. Catal. B Environ.*, vol. 342, no. September 2023, p. 123401, 2024, doi:10.1016/j.apcatb.2023.123401.
92. K. Paździor, L. Bilińska, and S. Ledakowicz, “A review of the existing and emerging technologies in the combination of AOPs and biological processes in industrial textile wastewater treatment,” *Chem. Eng. J.*, vol. 376, no. December 2018, p. 120597, 2019, doi:10.1016/j.cej.2018.12.057.
93. W. Sun et al., “Ultraviolet (UV)-based advanced oxidation processes for micropollutant abatement in water treatment: Gains and problems,” *J. Environ. Chem. Eng.*, vol. 11, no. 5, 2023, doi:10.1016/j.jece.2023.110425.
94. Y. Huang, M. Li, Z. Sun, W. Li, J. R. Bolton, and Z. Qiang, “Facilitated prediction of micropollutant degradation via UV-AOPs in various waters by combining model simulation and portable measurement,” *Engineering*, vol. 37, no. 3, pp. 87–95, 2024, doi:10.1016/j.eng.2023.10.009.
95. W. Ma et al., “Overview of enhancing biological treatment of coal chemical wastewater: New strategies and future directions,” *J. Environ. Sci. (China)*, vol. 135, pp. 506–520, 2024, doi:10.1016/j.jes.2022.11.008.
96. A. Simões, R. Macêdo-júnior, B. Santos, L. Silva, and D. Ruzene, “Produced water : An overview of treatment technologies,” *Int. J. Innov. Educ. Res.* vol. 8, no. 4, pp. 207–224, 2020.
97. A. Khalidi-Idrissi et al., “Recent advances in the biological treatment of wastewater rich in emerging pollutants produced by pharmaceutical industrial discharges,” *Int. J. Environ. Sci. Technol.*, vol. 20, no. 10, pp. 11719–11740, 2023, doi:10.1007/s13762-023-04867-z.
98. J. S. Sravan, L. Matsakas, and O. Sarkar, “Advances in biological wastewater treatment processes: Focus on low-carbon energy and resource recovery in biorefinery context,” *Bioengineering*, vol. 11, no. 3, 2024, doi:10.3390/bioengineering11030281.
99. R. Sathya, M. V. Arasu, N. A. Al-Dhabi, P. Vijayaraghavan, S. Ilavenil, and T. S. Rejiniemon, “Towards sustainable wastewater treatment by biological methods: A challenges and advantages of recent technologies,” *Urban Clim.*, vol. 47, no. October 2022, p. 101378, 2023, doi:10.1016/j.uclim.2022.101378.
100. A. Singla, “Review of biological treatment solutions and role of nanoparticles in the treatment of wastewater generated by diverse industries,” *Nanotechnol. Environ. Eng.*, vol. 7, no. 3, pp. 699–711, 2022, doi:10.1007/s41204-022-00267-9.
101. M. A. Musa and S. Idrus, “Physical and biological treatment technologies of slaughterhouse wastewater: A review,” *Sustainability*, vol. 13, no. 9, pp. 1–20, 2021, doi:10.3390/su13094656.
102. H. Wen, D. Cheng, Y. Chen, W. Yue, and Z. Zhang, “Review on ultrasonic technology enhanced biological treatment of wastewater,” *Sci. Total Environ.*, vol. 925, no. November 2023, p. 171260, 2024, doi:10.1016/j.scitotenv.2024.171260.
103. S. Moftakhari Anasori Movahed, L. Calgaro, and A. Marcomini, “Trends and characteristics of employing cavitation technology for water and wastewater treatment with a focus on hydrodynamic and ultrasonic cavitation over the past two decades: A Scientometric analysis,” *Sci. Total Environ.*, vol. 858, no. July 2022, p. 159802, 2023, doi:10.1016/j.scitotenv.2022.159802.
104. A. El Jery et al., “An application of ultrasonic waves in the pretreatment of biological sludge in urban sewage and proposing an artificial neural network predictive model of concentration,” *Sustainability*, vol. 15, no. 17, 2023, doi:10.3390/su151712875.
105. H. Yuan, S. Zhai, H. Fu, Z. Li, D. Gao, and H. Zhu, “Environmental and economic life cycle assessment of emerging sludge treatment routes,” *J. Clean. Prod.*, vol. 449, no. December 2023, p. 141792, 2024, doi:10.1016/j.jclepro.2024.141792.

Degradation of Organic Contaminants in Wastewater via Hydrodynamic Cavitation Technology

5

Ashok Kumar Babuchellam,
Thirumarai Selvi Chandraraju,
MuthuKrishnan Mayakrishnan, and
Hariprasad Perumal

5.1 INTRODUCTION

Wastewater management has become a pressing global concern due to the increasing release of organic pollutants into aquatic environments. These pollutants include medications, pesticides, dyes, and industrial chemicals. Environmental and human health is jeopardized because these pollutants frequently evade standard remediation methods. There is an immediate need for new and improved methods of degrading these chemical molecules [1].

As a new, cost-effective, and energy-efficient way to break down organic contaminants, hydrodynamic cavitation (HC) technology is showing great promise as a wastewater treatment alternative. Cavitation is the reaction of a liquid to rapid variations in pressure that causes microbubbles or cavities to form, grow, and then collapse. In addition to the highly reactive hydroxyl radicals (OH), localized high temperatures (up to 5,000 K) and pressures (over 1,000 atm) are produced by the sudden collapse of these bubbles. By oxidizing and decomposing complex organic molecules into smaller, less toxic ones, these radicals can facilitate their removal from water [2].

There are a number of benefits to using HC as an advanced oxidation method rather than alternatives like chemical oxidation or ultraviolet light. Its ability to operate at ambient temperature and humidity without the need for extra chemicals or high-energy inputs makes it more eco-friendly and versatile for

usage in large-scale industrial settings [3]. When combined with other treatment procedures, like chemical or biological processes, HC can further increase overall efficiency and contaminant removal rates [4].

Many researchers are interested in HC as a means of degrading organic pollutants since it is a sustainable and scalable method for improving wastewater quality [5,6]. In what follows, this research will introduce HC, describe its mechanism of action for removing organic contaminants, and discuss potential applications of HC in various wastewater treatment scenarios.

5.2 CAVITATION AND ITS CLASSIFICATION

Cavitation is a phenomenon where vapor bubbles form and collapse in a liquid due to pressure fluctuations. These bubble collapses generate extreme localized conditions, such as temperatures up to 5,000 K and pressures as high as 1,000 atm [7]. These intense conditions make cavitation a valuable tool for industrial applications, particularly in advanced oxidation processes (AOPs). In the context of wastewater treatment, cavitation's ability to produce hydroxyl radicals (OH) plays a key role in the oxidation and degradation of complex organic contaminants [8].

5.2.1 Classification of Cavitation

Cavitation can be categorized based on the method of its induction. The two primary forms of cavitation are **acoustic cavitation** and **hydrodynamic cavitation**, each with distinct applications and mechanisms [9].

5.2.2.1 Acoustic cavitation

Acoustic cavitation is induced by applying high-frequency ultrasonic waves to a liquid. These waves create alternating high- and low-pressure cycles that cause cavitation bubbles to form during the rarefaction phase and collapse during the compression phase [10]. Acoustic cavitation is used in sonochemistry, where the cavitation-induced chemical reactions accelerate reaction rates [11]. It is also employed in cleaning applications, as the collapse of cavitation bubbles generates micro-jets that remove dirt and contaminants from surfaces [12]. However, the small-scale nature of this process limits its industrial utility. Precision control over cavitation makes it suitable for small-scale, high-precision applications [13]. Due to the localized nature of cavitation formation and the high-energy requirements of ultrasound, scaling up acoustic cavitation for large wastewater treatment systems is less feasible [14].

5.2.2.2 HC

HC is generated by passing a liquid through a constriction (e.g., Venturi tubes, orifice plates) that induces a rapid drop in pressure. When the liquid's pressure falls below its vapor pressure, vapor-filled cavities form. As the liquid exits the constriction, these bubbles collapse under higher pressure, generating intense heat, shock waves, and reactive species such as hydroxyl radicals. HC has emerged as a highly effective method for degrading persistent organic pollutants in wastewater [15]. Unlike conventional treatment techniques, which may struggle with resistant compounds like pharmaceuticals, pesticides, and dyes, HC generates powerful oxidizing radicals that can break down these bio-refractory compounds into simpler, less harmful substances [16]. HC has been used in the treatment of wastewater containing azo dyes from textile industries. Azo dyes, which are highly stable and resistant to biological degradation, can be effectively broken down using HC [17]. Studies have shown significant reductions in both color and chemical oxygen demand (COD) through the oxidation of the dye molecules under cavitation conditions [18].

HC systems are easily scalable and can be integrated into continuous flow systems, making them ideal for large-scale wastewater treatment [19]. Unlike acoustic cavitation, HC does not require an external energy source like ultrasound; instead, it utilizes the kinetic energy of fluid flow, making it more energy-efficient. As the process can be designed to operate under ambient temperature and pressure conditions, it reduces operational costs compared to other AOPs like UV or ozone treatment [20].

HC can be combined with other treatment processes to enhance overall pollutant degradation. For instance, adding oxidants such as hydrogen peroxide (H_2O_2) or integrating Fenton chemistry ($\text{Fe}^{2+}/\text{H}_2\text{O}_2$ system) can increase the generation of hydroxyl radicals and further improve contaminant breakdown [21].

5.2.2.3 Other forms of cavitation

Optical cavitation, generated by the rapid deposition of energy from focused laser pulses, induces the formation of vapor bubbles through localized heating. This phenomenon is typically observed in highly controlled experimental environments and is primarily employed for scientific research rather than practical industrial applications due to its considerable energy demands. The localized heating results in temperatures exceeding several thousand Kelvin within the bubble core, causing extreme pressure gradients [22]. Such conditions have proven valuable for studying high-energy processes in fluids and biological tissues, but the cost and complexity of high-powered laser systems make optical cavitation less feasible for large-scale industrial use.

On the other hand, vortex cavitation occurs in the swirling flows of vortices, such as those found in pumps, turbines, or marine propellers. This form of cavitation is generally unintentional and problematic in industrial and hydraulic systems. The rapid pressure drops within vortices lead to the formation of vapor cavities, which collapse as they move into higher-pressure regions. This collapse produces intense shock waves, causing material erosion, noise, and vibration, which can significantly reduce the efficiency and lifespan of hydraulic equipment [23]. In pump systems, vortex cavitation can reduce efficiency by up to 10%–15%, leading to both energy losses and increased maintenance costs. Consequently, engineers aim to minimize vortex cavitation through careful design, often incorporating anti-cavitation techniques like altering impeller geometry or modifying flow conditions.

5.2.3 Mechanisms of HC in Wastewater Treatment

HC's effectiveness in degrading organic contaminants stems from the intense conditions generated during bubble collapse. The collapse of cavitation bubbles produces shock waves, localized high temperatures, and pressures, as well as hydroxyl radicals [24]. These radicals initiate a series of chemical reactions that break down complex organic compounds into smaller, less toxic molecules.

5.2.3.1 Bubble dynamics

As the liquid passes through the constriction in a HC reactor, vapor bubbles form due to the rapid drop in pressure. These bubbles then move to areas of higher pressure, where they implode, releasing intense energy [25]. This process generates micro-jets and shock waves, which create turbulence and shear forces, contributing to the physical breakdown of organic materials [26]. The mechanism of the bubble dynamics is explained as follows (a) **Formation of Cavitation Bubbles:** In a HC reactor, the liquid flows through a constriction (such as an orifice or Venturi), leading to a rapid decrease in pressure below the vapor pressure of the liquid. This causes the formation of vapor bubbles or cavities within the liquid. These bubbles are small, typically ranging from 10 to 100 μm in diameter, depending on the flow rate and reactor geometry. (b) **Movement and Collapse of Bubbles:** After formation, the bubbles move downstream to regions of higher pressure. As the pressure rises above the vapor pressure, the bubbles implode violently. The collapse of these vapor cavities can generate local temperatures of around 5,000 K and pressures exceeding 1,000 atm. These extreme conditions lead to the release of substantial energy in the form of shock

waves and micro-jets, which contribute to several effects, such as surface cleaning, chemical reactions, and physical disintegration of materials. The mechanical effects of cavitation—namely, turbulence, shear forces, and high-energy shock waves—contribute to the physical disintegration of organic materials such as pollutants and biomass. In wastewater treatment, for example, these forces help break down complex organic molecules into simpler compounds, making them easier to degrade biologically. The implosion of cavitation bubbles also causes the generation of micro-jets, which are high-velocity liquid streams directed toward surfaces in close proximity to the collapsing bubble. The velocity of these micro-jets can exceed 100 m/s, generating intense shear forces and localized turbulence. These physical forces are instrumental in the breakdown of organic materials and the disruption of cell walls in biological matter. In addition, they enhance the mixing and diffusion processes, improving mass transfer and promoting chemical reactions.

5.2.3.2 Chemical reactions

When cavitation bubbles implode, they release extreme energy, creating high local temperatures (up to 5,000 K) and pressures (greater than 1,000 atm). This violent collapse produces reactive species, particularly hydroxyl radicals ($\bullet\text{OH}$), through the dissociation of water molecules. These radicals are among the most powerful oxidizing agents, capable of attacking and breaking the carbon–carbon bonds in organic pollutants.

One of the key reactions occurring during this process is the oxidation of complex organic molecules. The hydroxyl radicals target these molecules, initiating a chain reaction that breaks down large, stable compounds into smaller, more manageable substances. For instance, aromatic rings present in pesticides, pharmaceuticals, or other industrial chemicals can be oxidized into smaller aliphatic compounds, which are more biodegradable and easier to remove from wastewater through biological treatment methods [27].

In particular, pollutants containing benzene rings or polycyclic aromatic hydrocarbons (PAHs), which are highly resistant to conventional treatment, can be effectively degraded by the hydroxyl radicals generated during cavitation. The process can convert these toxic compounds into less harmful byproducts like carboxylic acids or even fully mineralize them into carbon dioxide and water, reducing their environmental impact. The efficiency of the oxidation process depends on factors such as (a) Cavitation reactor design (e.g., orifice plates, Venturi tubes), (b) Flow conditions (pressure and velocity) (c) Temperature and pH of the medium, and (d) Presence of catalysts or additional oxidizing agents like hydrogen peroxide. Table 5.1 provides an overview of typical cavitation-induced chemical reactions involved in the degradation of organic pollutants, as reported by Patil et al. [28].

5.2.3.3 Combination with oxidants

To enhance the degradation of organic pollutants, HC can be effectively combined with oxidants such as hydrogen peroxide (H_2O_2) and catalysts like ferrous ions (Fe^{2+}) to promote Fenton reactions. This combination leverages the strengths of both processes, resulting in a significant increase in the production of reactive hydroxyl radicals ($\bullet\text{OH}$), which are crucial for the oxidation of recalcitrant compounds.

TABLE 5.1 Typical Cavitation-Induced Chemical Reactions for Organic Pollutants [28]

POLLUTANT	REACTIVE SPECIES	PRIMARY REACTION	BYPRODUCTS
Aromatic hydrocarbons	$\bullet\text{OH}$	Oxidation of aromatic rings	Aliphatic acids, CO_2 , H_2O
Chlorinated solvents	$\bullet\text{OH}$, O_3	Dechlorination and ring cleavage	Smaller, less toxic compounds
Pesticides (e.g., atrazine)	$\bullet\text{OH}$	Oxidation of nitrogen and carbon bonds	Simpler organics, nitrates
Industrial dyes (e.g., MB)	$\bullet\text{OH}$	Oxidative cleavage of azo bonds	CO_2 , NH_3 , smaller organics

In a typical Fenton reaction, ferrous ions catalyze the decomposition of hydrogen peroxide, generating hydroxyl radicals:



This reaction not only enhances the generation of hydroxyl radicals but also helps to regenerate ferrous ions, creating a cycle that sustains radical production. The presence of additional hydroxyl radicals dramatically improves the degradation efficiency of complex pollutants, such as phenolic compounds, dyes, and pesticides, which are often resistant to conventional treatment methods [29].

The combination of HC with oxidants like hydrogen peroxide and ferrous ions significantly enhances the degradation of organic pollutants through several mechanisms. First, while cavitation generates hydroxyl radicals, the presence of hydrogen peroxide and ferrous ions substantially increases their concentration, leading to more aggressive oxidation. Additionally, the turbulence and micro-jets produced during cavitation improve the mixing of reactants, ensuring effective interaction between the oxidants and the pollutants. This synergy allows for the breakdown of complex organic molecules, such as aromatic compounds, into smaller, more biodegradable components, or even complete mineralization into carbon dioxide and water [30].

5.2.4 Applications of HC in Wastewater Treatment

5.2.4.1 Treatment of textile wastewater

Textile industries generate substantial volumes of wastewater laden with dyes, detergents, and heavy metals, which can pose severe environmental challenges. Among these pollutants, azo dyes are particularly concerning due to their resistance to conventional biological treatment methods. HC has emerged as an effective technology for degrading such persistent dyes. For instance, Thakur et al. [31] demonstrated that HC could significantly degrade azo compounds, leading to improved treatment outcomes. The effectiveness of this method is notably enhanced when combined with hydrogen peroxide, which generates additional hydroxyl radicals during the cavitation process. This synergistic effect not only accelerates dye removal rates but also reduces the toxicity of the treated effluent. Studies have reported substantial reductions in color and toxicity levels, making this combined approach a promising solution for managing wastewater from textile industries. By integrating HC with oxidants, industries can achieve more sustainable practices, mitigating the environmental impact of their wastewater discharges [31].

5.2.4.2 Degradation of pharmaceuticals

Pharmaceutical residues, particularly antibiotics, are frequently detected in municipal wastewater, posing significant risks to aquatic ecosystems and public health. The presence of these contaminants can lead to the development of antibiotic-resistant bacteria and disrupt natural biological processes. HC has emerged as a promising technology for breaking down these complex pharmaceutical molecules, thereby preventing their accumulation in the environment. Dehghani and Mahvi [32] demonstrated that HC could effectively degrade a range of antibiotics, including ciprofloxacin and amoxicillin. These studies indicate that cavitation-based processes can significantly reduce the concentration of these harmful compounds in wastewater. Khan and Gogate [33] further highlighted that the combination of HC with other treatment methods, such as AOPs, enhances the degradation efficiency, leading to more complete mineralization of the antibiotics into less toxic byproducts. This approach not only mitigates the environmental impact of pharmaceutical residues but also supports the development of more sustainable wastewater treatment practices.

5.2.4.3 Treatment of pesticide-contaminated water

Pesticides and herbicides, widely utilized in agriculture, frequently leach into nearby water bodies, posing significant environmental and health risks. These contaminants can disrupt aquatic ecosystems and

may pose long-term risks to human health through water consumption. HC has emerged as an effective method for degrading pesticide residues, such as atrazine and dichlorvos. This process generates reactive hydroxyl radicals, which are powerful oxidizing agents capable of breaking down complex organic compounds. Studies have shown that HC can effectively oxidize these harmful pesticides, converting them into less toxic or harmless byproducts. For example, Petkovšek and Dular [34] demonstrated that cavitation treatment significantly reduced the concentration of atrazine and dichlorvos in contaminated water, with degradation rates reaching over 90% in some cases. The application of this technology not only enhances the overall quality and safety of water resources but also supports sustainable agricultural practices by mitigating the impact of pesticide runoff. This approach provides an innovative and environmentally friendly solution to combat pesticide pollution, highlighting the importance of AOPs in wastewater treatment.

5.3 HC REACTORS

HC reactors have emerged as powerful and energy-efficient tools for wastewater treatment, leveraging the principles of cavitation to generate extreme localized conditions that facilitate the breakdown of complex organic pollutants. These reactors operate based on the controlled collapse of cavitation bubbles, which creates intense temperatures (up to 5,000 K) and pressures (greater than 1,000 atm) within the liquid medium. This rapid collapse generates reactive hydroxyl radicals ($\bullet\text{OH}$), which are highly effective in oxidizing persistent organic compounds, including dyes, pesticides, and pharmaceutical residues. HC reactors have found successful applications across various fields, particularly in wastewater treatment, water purification, and food processing. In wastewater treatment, these reactors effectively degrade complex organic pollutants found in industrial effluents, improving effluent quality and reducing environmental impact. Studies have shown significant removal efficiencies for a range of contaminants, including dyes and pharmaceuticals, through the generation of reactive hydroxyl radicals during cavitation [35]. Additionally, HC is employed in water purification to remove contaminants from drinking water sources, offering an innovative approach to enhance water quality. In the food processing industry, these reactors enhance extraction processes by breaking down cell walls in plant materials, leading to improved yield and efficiency in extracting valuable compounds [36]. The versatility and effectiveness of HC make it a promising technology for diverse applications, contributing to sustainability and efficiency across sectors.

5.3.1 Working Principle of HC

HC is created when a liquid is forced through a constriction (such as a Venturi tube, orifice plate, or nozzle), causing a rapid drop in pressure. When the local pressure drops below the vapor pressure of the liquid, vapor-filled cavities or bubbles form. These bubbles then collapse violently as the liquid flows to regions of higher pressure downstream, generating shock waves, micro-jets, and extreme local conditions [37]. The energy released during the bubble collapse creates localized high temperatures (up to 5,000 K) and pressures (up to 1,000 atm), which can break down pollutants through mechanical shear forces and radical-induced oxidation [38]. The collapse of cavitation bubbles also produces highly reactive hydroxyl radicals ($\text{OH}\cdot$), which initiate the degradation of organic compounds. These radicals oxidize organic molecules, breaking down complex pollutants such as dyes, pharmaceuticals, and pesticides into simpler, less harmful substances. The efficiency of pollutant degradation depends on several factors, including the reactor design, cavitation number, and operating conditions [39].

5.3.2 Types of HC Reactors

5.3.2.1 Venturi-type HC reactor

The **Venturi-type HC reactor** is one of the most commonly used designs due to its simplicity and efficiency in generating cavitation. It consists of a constriction, typically in the form of a converging-diverging nozzle (Venturi tube), through which the liquid flows. The velocity of the liquid increases significantly as it passes through the constriction, causing a rapid drop in pressure that results in the formation of cavitation bubbles. These bubbles collapse downstream, creating intense local conditions, such as high temperatures and pressures, which are effective in degrading pollutants. Venturi reactors are energy-efficient and can handle large flow rates. They are less prone to fouling and clogging and are easy to scale up for industrial applications. The geometry needs to be carefully designed to maintain the necessary flow and pressure conditions. Cavitation erosion can occur over time, leading to wear on the reactor surfaces [19].

5.3.2.2 Orifice-type HC reactor

The orifice-type HC reactor utilizes one or more orifice plates to generate cavitation. In this setup, the liquid is forced through small holes in the orifice plates at high velocity, leading to a sharp drop in pressure. This pressure drop enables the formation of cavitation bubbles, which then collapse as the liquid flows into regions of higher pressure downstream. Orifice reactors are known for their simple design and effectiveness in creating high-intensity cavitation. They are particularly advantageous for treating highly polluted wastewater containing organic dyes, heavy metals, and various industrial contaminants [40].

However, orifice plates come with certain drawbacks. They are more susceptible to clogging, especially when processing wastewater with high particulate loads, which can impede their functionality and reduce treatment efficiency. Additionally, there can be significant energy losses due to the pressure drop across the orifice, which may diminish the overall energy efficiency of the reactor [41]. Addressing these challenges is crucial for optimizing the performance of orifice-type HC reactors in practical applications.

5.3.2.3 Rotating-type HC reactors

Rotating HC reactors employ rotating components, such as impellers or disks, to induce cavitation. The rotation generates high shear forces and centrifugal effects, creating regions of low pressure where cavitation occurs. As the liquid moves to areas of higher pressure, the collapse of these cavitation bubbles produces intense mechanical and chemical effects, enhancing the degradation of pollutants. Rotating reactors can generate high-intensity cavitation and are highly effective at inducing turbulence, providing more control over the cavitation process. This makes them particularly suitable for applications that require mixing and agitation, such as the degradation of complex pollutants [42]. Despite their advantages, rotating systems come with challenges. They are mechanically more complex, requiring regular maintenance to ensure optimal performance. The wear and tear on moving parts can lead to higher operational costs over time, and scaling up these systems for industrial applications presents additional difficulties [43]. Addressing these challenges is essential for the successful implementation of rotating HC reactors in various treatment processes.

5.3.2.4 Vortex-based HC reactors

In vortex-based HC reactors, cavitation is generated by inducing a strong swirling or vortex motion in the liquid. This is typically accomplished using specialized nozzles or chambers designed to create a distinct vortex flow pattern. The centrifugal forces created within the vortex lead to regions of low pressure where cavitation bubbles can form and subsequently collapse. Vortex-based reactors are effective at generating a

TABLE 5.2 Comparison of Different HC Reactors [48]

REACTOR TYPE	ENERGY EFFICIENCY	CAVITATION INTENSITY	FOULING/ CLOGGING	EASE OF SCALE-UP	COMPLEXITY
Venturi reactor	High	Moderate	Low	High	Low
Orifice reactor	Moderate	High	High	Moderate	Low
Rotating reactor	Moderate	High	Low	Low	High
Vortex-based reactor	Moderate	High	Moderate	Moderate	Moderate
Hybrid cavitation reactor	Low	Very High	Depends on setup	Low	High

large number of cavitation bubbles, providing high turbulence that enhances their suitability for treating heavily polluted wastewater. Additionally, these reactors can operate at lower flow rates while still maintaining efficient cavitation [44–46].

However, the design and optimization of vortex reactors can be more complex compared to other types of cavitation reactors. They require precise control of flow dynamics to maintain cavitation intensity, which can pose challenges in scaling up for industrial applications. Ensuring optimal performance in vortex-based reactors necessitates a thorough understanding of the fluid dynamics involved and careful engineering to achieve the desired treatment outcomes.

5.3.2.5 Other types of HC reactors

Several other types of HC reactors have been developed for specific applications. Some of them are (a) **Hydraulic cavitation devices**: These reactors utilize hydraulic systems to generate cavitation, effectively producing a uniform bubble distribution. This uniformity is critical for achieving consistent treatment results across various applications, including wastewater treatment and material processing [47]. (b) **Jet cavitation reactors**: In jet cavitation systems, high-speed liquid jets create localized pressure drops in the target medium to generate cavitation. These systems are particularly effective in breaking down biofilms and other persistent contaminants, significantly improving the efficiency of water treatment processes [48]. (c) **Hybrid cavitation reactors**: These reactors combine HC with other AOPs, such as sonochemical, chemical, or photocatalytic methods. This synergy enhances the breakdown of complex pollutants, making hybrid reactors an appealing option for diverse environmental applications [49]. The comparison of different HC reactors are discussed in Table 5.2.

5.4 EFFECT OF OPERATING PARAMETERS OF HC

The performance and efficiency of HC reactors are significantly influenced by various operating parameters. Understanding these factors is crucial for optimizing the degradation of pollutants and enhancing the overall effectiveness of wastewater treatment processes. Key operating parameters include temperature, pH of the solution, initial concentration of fluids, fluid velocity, inlet and outlet pressure, cavitation number, and reactor design.

5.4.1 Effect of Temperature

Another important element that influences the cavitation yield and, consequently, the degradation efficiency is the effect of temperature on the degradation rate. In several respects, it affects the rate at which pollutants degrade. The ideal temperature for operation is mostly determined by the boiling point and vapor pressure of the medium and contaminant. Because the transformation rate of liquid into vaporous cavities

is faster at high operating temperatures and the pressure needed to evaporate the liquid is lower, this might facilitate the development of cavities [50]. As the temperature rises, the amount of gas dissolved in the solution will also decrease, resulting in a reduction of cavity nuclei available for cavitation generation. Additionally, when the temperature rises, more water vapor will fill the cavitation bubbles, strengthening the cavitation action and improving the cushioning effect. On the other hand, the deterioration efficiency would be reduced at low temperatures due to a lower transformation rate [51]. Furthermore, temperature has an impact on the viscosity, and surface tension of a liquid, all of which can alter the dynamics of cavities and their cavitation behavior. Additionally, greater temperatures result in increased thermal energy consumption and higher running expenses. According to all of this research, it is possible to identify the ideal temperature, but this much relies on the particular pollutant. Because of this, there are several reports about the impact of operating temperature. Panda and Manickam [52] conducted studies in the temperature range of 20–40°C, maintaining a dicofol concentration of 50 mg/L, an intake pressure of 5 bar, and a solution pH of 3 in order to examine the impact of solution temperature on the degradation rate of dicofol. The optimum temperature for the fastest rate of degradation, according to the data, was 30°C. Lu et al. [53] investigated how temperature affected the amount of bisphenol A removed by varying the temperature while maintaining other variables including treatment duration, intake pressure, and bisphenol A concentration. It is evident that the removal rate rises with temperature at first, peaking at 35°C, then falling at 40°C. At the optimal temperature of 35°C, a maximum removal rate of 25% was achieved. As the temperature rises, the saturated vapor pressure of the liquid rises as well, which reduces the difference between the liquid flow pressure and saturated vapor pressure and facilitates the formation of cavitation. The dissolved gas quantity in water and the vaporization core both decrease with increasing temperature, which lessens the cavitation impact. Patil et al. [54] reported that the operating temperature had no significant impact on the rate of imidacloprid degradation. The impact of pollutants in collapsing cavities will not be dominant since imidacloprid has a boiling point higher than water. Consequently, there is no standard guideline for determining how temperature affects the breakdown of various contaminants; instead, it should be determined by comparing the boiling temperatures of water and the degraded materials.

5.4.2 Effect of Initial pH of the Solution

According to research in the literature, the pH of the solution has a significant impact on how quickly pollutants degrade. Typically, the pH of any pollutant solution is adjusted using sulfuric acid, sodium hydroxide, or potassium hydroxide. It is noteworthy that the majority of research examined the impact of the solution's initial pH on the degree of degradation in order to optimize the process parameters. Ye et al. [55] used a cavitating device with a circular Venturi base to study the degradation of rhodamine B. Under 25°C working conditions, with an initial concentration of 10 ppm of rhodamine B, a volume of 4 L, and an inlet pressure of 4 bar, the study employed a solution pH range of 1–6. It was found that when a circular Venturi was utilized as the cavitating device, the amount of rhodamine B degradation was greater at low pH values than at higher pH values. In terms of quantifiable deterioration, a pH 3 solution yielded 38.7%, whereas a pH 6 solution showed 19.2% degradation after 120 minutes of processing. Roy and Moholka [56] investigated the removal of p-nitrophenol at three different pH levels: 3, 7, and 10, with the best loading of Fenton catalysts. It was discovered that at pH 3, 7, and 11, the apparent degradation decreases with increasing pH as it is 78.8%, 72.6%, and 66.1%, respectively. The findings are in agreement with those of Pradhan and Gogate [57], who observed p-nitro phenol removals at pH values of 3.75 and 8.0, respectively, with a maximum of 63.2% and a minimum of 35.7%. In contrast to the previous findings, Wang et al. [58] found that tetracycline hydrochloride (TC) could be removed up to 82.3% at pH 9.2 in 120 minutes when HC (Venturi) and photocatalysis were used. Authors justified that, TC is less stable in alkaline environments than in acidic ones. Oxidizing or converting carbocyclic ring-opening isomers into other compounds was easier. So, it can be claimed that the initial solution pH may be adjusted to be either highly basic (for some chemicals that are unstable in alkaline circumstances) or very acidic (usually) to promote organic breakdown.

5.3.3 Effect of Initial Concentration of Contaminant

Another significant factor influencing the rate at which pollutants degrade is the starting concentration of contaminant molecules. Numerous research [59,60] have found that degrading efficiency is inversely related to the starting concentration of contaminants in terms of percentage decrease. This is mostly due to the fact that, in some circumstances, the HC effect's production of free radicals is restricted. There may not be enough hydroxyl radicals ($\bullet\text{OH}$) generated to fully destroy the organic matter as the concentration of contaminants rises, which would lead to a slower removal rate. The concentration of contaminants, or COD, in the actual industrial effluent is often high. Dilution is frequently required to achieve improved removal efficiency. Dilution, on the other hand, would greatly increase the overall amount of wastewater, use more energy, and take up more structural space, all of which would raise the cost of treatment. As a result, it is critical to establish the proper initial concentration or dilution ratio, and several studies have documented the impact of the contaminants' initial concentration. Using a slit Venturi, Rajoriya et al. [61] investigated the impact of rhodamine 6G (Rh6G) starting concentration on the decolorization rate within the range of 10–50 ppm. According to reports, the decolorization rate falls as the initial concentration rises because not enough $\bullet\text{OH}$ radicals are generated to break down the dye. This indicates that the relevant ratio of $\bullet\text{OH}$ radicals to dye molecules is an important aspect. Similar results were noted by Malade and Deshannavar [59], who found that degradation rate constant of Reactive Red 120 dropped when the starting concentration increased from 10 to 25 mg/L. On the one hand, although the total concentration of $\bullet\text{OH}$ in the system remains constant, the total number of dye molecules grows with the initial concentration. On the contrary, the rate constant drops as a result of the intermediates created during decolorization competing with the dye for $\bullet\text{OH}$. Sometimes, the rate of deterioration is not directly correlated with the initial concentration of contaminants. The presence of the ideal value for the starting concentration of pollutants has been shown in some publications. Panda and Manickam [52] conducted a number of studies on the impact of the initial concentration of dicofol on the rate of degradation. They discovered that when the initial dicofol content is higher than the ideal value of 50 mg/L, the degree of degradation reduces. The saturation of the cavity interfacial region at a greater dicofol concentration is responsible for the observed drop in degradation above the optimal value, and the radicals produced by HC are insufficient to oxidize all contaminants. Overall, it can be said that the qualities of the degraded chemicals and the process requirements should be taken into consideration when determining the concentration.

5.3.4 Effect of Cavitation Number

The cavitation number and input pressure have a significant influence on the number of cavities formed as well as the cavitation intensity (collapse pressure magnitude). It is crucial to examine the hydraulic characteristics of all cavitating devices, including Venturi and orifice, in order to calculate the effects of pressure and flow. Cavitation number (C_v), which may be computed using Eq. (5.1), is typically used to quantify the degree and cavitation intensity [62,63].

$$C_v = (p_2 - p_v) / (1/2) \rho v^2 \quad (5.1)$$

where p_v is the liquid's vapor pressure at the specified operating temperature, ρ is the liquid density, and v is the velocity at the constriction, which may be computed using the flow rate and orifice/throat diameter, where p_2 is the completely recovered downstream pressure. The literature study and Eq. (5.1) analysis showed that raising the input pressure reduces the cavitation number, which causes more cavitation events to occur in the reactor and greater collapse intensity, which ultimately drives higher deterioration. Increased fluid flow via the main pipeline is directly proportional to increased Venturi and orifice intake pressure. Consequently, there is an increase in the fluid velocity at the orifice or Venturi opening, which lowers the cavitation numbers (Eq. 5.1) and promotes the formation of cavities, the collapse of which causes a greater degree of degradation. A few significant ones are discussed for a more quantitative understanding.

Vichare et al. [64] used an orifice plate to investigate the impact of cavitation number on iodine liberation. In all, six distinct orifice plate designs were employed in the investigation. It was noted that increased input pressure was associated with a lower cavitation number, which in turn led to more intense cavitation. For instance, decreasing the cavitation number from 0.59 to 0.04 (plate 1), 0.55–0.04 (plate 2), 1.9–0.3 (plate 3), 5.6–0.4 (plate 4), 1.1–0.3 (plate 5), and 0.8–0.1 (plate 6) was the outcome of raising the input pressure from 20 to 80 psig. Furthermore, for all of the orifice plates, iodine liberation was greater at the lower cavitation number. Weng et al. [65] also found that in the case of a multiple-hole orifice plate (with 9 holes and 1.5 mm for each hole's diameter), the cavitation number drops from 0.76 to 0.19 with an increase in input pressure from 0.3 to 0.7 MPa. There are several additional evidences found in the literature that show comparable outcomes for the cavitation number effect [66–68]. Key points about how the cavitation number affects target compound degradation include: (a) Cavitation number decreases with increasing inlet pressure, which also results in higher degradation; (b) Venturi produces lower cavitation numbers than orifice plates, which again results in better degradation for Venturi; (c) The geometry and specifications of orifice plates and Venturi determine the cavitation number; and (d) The ideal cavitation number is usually observed in the range of 0.15–0.4, with much lower values of cavitation number giving super cavitation.

5.3.5 Effect of the Inlet and Outlet Pressure of the HC Reactor

The most crucial operational parameter that has the ability to drastically change the bubble or cavitation behavior and cavitation intensity is the input pressure of the cavitation devices. The rate of change of the turbulent pressure in the orifice's downstream portion and the final magnitude of the recovered pressure downstream of the orifice are the primary determinants of the cavity collapse intensity. A higher permanent pressure drop across the orifice and an increase in the power input per unit mass of liquid result from an increase in the pressure upstream of the orifice, which also increases the downstream pressure, liquid flow rate, and energy dissipation rate into the system [69]. The number of cavities will decrease as the velocity and liquid flow increase [70]. Gogate and Pandit [71] stated that as the inlet pressure rises, the resulting collapse pressure of the cavities also increases. Kumar and Pandit [72] reached a similar conclusion using a simplified and unified model to analyze the impact of inlet pressure on the Venturi. For a given pressure drop, it is observed that the intensity of the cavity cluster's collapse rises as the inlet pressure increases. This is explained by the fact that the cavity collapses more violently due to the high input pressure, the huge pressure drop across the Venturi, and the rate of energy dissipation and turbulence intensities. The literature's HC simulations' findings [73] show that the C_v falls with increasing input pressure. However, a rise in the quantity of cavities created and collapsing per unit of time typically is associated with a drop in the C_v [74]. Therefore, the combined impact of the C_v , which influences both the intensity of cavitation and the number of cavities created, will be the total effect of the input pressure on the cavitation yield.

The number of liquid passes under the same treatment period rises concurrently with an increase in intake pressure. This prolongs the residence time of the pollutants in the cavitation zone and accelerates their degradation. It is important to note that when the pressure reaches a certain threshold, super cavitation can occur, which is undesirable. According to several findings [53,64–66], there is an ideal pressure, and the amount of deterioration often exhibits a tendency to grow initially before decreasing with increased pressure. Using a single orifice, Gogate et al. [75] investigated the impact of the inlet pressure on the degradation of methyl parathion within the working range of 1–8 bar. It was discovered that the degree of degradation increases from 1 to 4 bar, the ideal pressure, and then decreases at higher pressures. Higher operating pressures cause the cavity to collapse more violently, which increases the pressure pulse that occurs when the cavity collapses. As a result, there are more hydroxyl radicals produced due to an increased degree of dissociation of water molecules. Nevertheless, the rate of deterioration decreases when pressure rises over the optimum 4 bar threshold. The reason for this might be that the beginning of hypercavitating circumstances reduces the amount of degradation since the bubbles develop

indiscriminately downstream of the constriction, forcing the flow to splash and evaporate. Thus, taking into account the overall effects of various factors, there is likely an optimal pressure, a conclusion supported by numerous studies [76–82]. According to published research, the ideal input pressure ranges for Venturi and orifice plates are 0.3–0.5 and 0.2–0.8 MPa, respectively. The considerable variation in the range of the ideal pressure for orifice plates might be attributed to the varying hole counts or diverse sizes and shapes of the holes.

The cavitation behavior can also be influenced by the outlet pressure of the HC reactor, in addition to the intake pressure of the HC devices. The impact of exit pressure on cavitation in the case of a constant pressure differential between the microchannel's intake and outlet was examined by Jin et al. [83]. The cavitation intensity was found to increase as the exit pressure decreased. The majority of research focused on the impact of the inlet pressure or the pressure drop between the HC reactors' inlet and outlet is found in the publications that are currently available. There are not many reports on the impact of outlet pressure. The constant outlet pressure that occurs when an outlet is linked to the atmosphere may be the cause of this. Examining how the outlet pressure affects cavitation behavior is required when the discharge is not into the atmosphere because downstream pressure increases in response to an increase in input pressure [84].

5.5 ANALYSIS OF HC REACTORS' ENERGY EFFICIENCY AND COST

In HC reactors, energy efficiency is defined as the ratio of the total energy input to the reactor to the effective energy utilized to achieve favorable cavitation effects, such as chemical reactions, emulsification, or pollutant degradation. It shows how effectively energy input is converted by the reactor into productive cavitation while energy losses due to inefficiencies such as turbulence, overheating, or supercavitation are minimized. Several investigations have documented the effectiveness of HC reactors fitted with various cavitation devices in terms of energy efficiency and cavitation yield, which measures the apparent degree of pollutant degradation per unit of energy delivered to the system. The primary energy-consuming part of the system is the pump, which circulates the pollutant solution through the cavitation chamber to be degraded [84]. Saharan et al. [85] analyzed the deterioration of orange-G, by comparing the energy efficiency of three cavitating devices: slit Venturi, circular Venturi, and circular orifice. The split Venturi was shown to have a larger cavitation yield due to its higher power dissipation when compared to the circular venturi and orifice.

Cost calculation is crucial as it determines the possible commercial application in addition to cavitation yield estimates. The cost of the chemical oxidants employed in the study as well as the cost analysis for treating actual effluent with HC in various combinations with additions was published by Raut-Jadhav et al. [86]. The treatment cost of HC alone was INR 10,250.99/m³, whereas the combination of hydrogen peroxide and HC resulted in a total cost of INR 1,951.63/m³. Consequently, it was determined that hydrogen peroxide in combination with HC was more economical than HC alone.

In addition, Thanekar et al. [77] calculated the overall expense of treating real wastewater with HC in conjunction with a number of sophisticated oxidation techniques. The overall cost of treatment with HC alone was INR 1.3/L; however, the combination techniques of HC+H₂O₂, HC+O₃, and HC+KPS yielded prices of INR 11.0/L, INR 1.1/L, and INR 3.6/L, respectively (the quoted costs include the expenditures necessary for the chemicals). A maximum cavitation yield of 0.04 mg/L and a total treatment cost of 11.5 Rs/L were recorded for the optimal HC+H₂O₂+O₃ treatment strategy, which was found to reduce COD to the greatest extent. Notably, in order to draw valid findings, the expenses presented in the study must be normalized in relation to the achieved COD decrease. When normalization is taken into account, it becomes clear that the combination of HC+H₂O₂+O₃ was far more effective than HC alone. This is evident even when treatment expenses are taken into account. The HC-based combination treatment

procedures guarantee the greatest cavitation production from the unit power source, as per Fedorov et al. [87]. Furthermore, compared to ultrasonic devices, energy may be dispersed uniformly in an HC reactor arrangement, which frequently results in improved energy efficiency.

5.6 METHODS FOR ASSESSING CAVITATION EFFICIENCY

Assessing the efficiency of HC in wastewater treatment is crucial for optimizing reactor performance and ensuring the effective degradation of pollutants. There are several methods to evaluate cavitation efficiency, typically based on the degree of pollutant degradation, energy consumption, and overall improvement in wastewater quality. Two key areas of assessment are wastewater pollutant degradation and biological wastewater treatments.

5.6.1 Wastewater Pollutant Degradation

The degradation of pollutants in wastewater through HC is often quantified using key parameters such as (a) COD, (b) total organic carbon (TOC), and (c) specific contaminant concentrations. **COD Reduction:** COD is used to measure the amount of organic pollutants in wastewater, representing the amount of oxygen required to oxidize these compounds. Studies have shown that HC, when combined with oxidants such as hydrogen peroxide (H_2O_2), can achieve COD reductions of 60%–90% in industrial wastewater treatments. For example, Bagal and Gogate [3] reported a COD reduction from 1,500 mg/L to less than 300 mg/L in textile wastewater when combining cavitation with Fenton's reagent (a mixture of H_2O_2 and iron salts). **(b) TOC Reduction:** TOC measures the amount of carbon in organic pollutants. Petkovšek and Dular [34] demonstrated that using HC could reduce TOC levels by 50%–80%. In their experiments with dye-contaminated wastewater, the TOC was reduced from 900 mg/L to around 180 mg/L when cavitation was coupled with oxidants like ozone. **(c) Specific Contaminant Degradation:** The removal of particular contaminants through cavitation is also well-documented. For instance, in the treatment of azo dyes, cavitation reactors have achieved degradation rates of 80%–95%. Patil et al. [88] showed that cavitation combined with H_2O_2 degraded 95% of a 100 mg/L concentration of methyl orange dye in wastewater over a treatment time of 60 minutes.

Kinetic Studies: The degradation kinetics of pollutants under HC often follows first-order or pseudo-first-order reaction kinetics. For example, studies have shown that the degradation rate constant for pollutants like azo dyes ranges from 0.05 to 0.15 minutes, depending on cavitation intensity and operating conditions [89]. Faster degradation rates were observed with the increase of input energy and the addition of oxidants.

Formation of Byproducts: Although HC effectively breaks down pollutants, it is essential to assess the byproducts formed during the process. Studies such as those by Kalumuck and Chahine [19] observed that intermediate compounds like aliphatic acids can form during the degradation of more complex molecules like pharmaceuticals. For instance, in the treatment of pesticides, degradation efficiency could be as high as 90%, but intermediate compounds may still persist, requiring further treatment to achieve full mineralization.

5.6.2 Biological Wastewater Treatments

In addition to pollutant degradation, HC has demonstrated significant potential in enhancing biological wastewater treatments by increasing the biodegradability of organic pollutants, making them more accessible to microorganisms. This is evident in the enhancement of biochemical oxygen demand (BOD), a key

measure of biodegradability. Cavitation effectively breaks down large, complex molecules into smaller and more accessible forms, increasing the BOD and indicating a higher potential for biological degradation [90]. In synergy with activated sludge systems, cavitation improves microbial activity by solubilizing particulate matter and releasing organic compounds, making them easier for microorganisms to metabolize. This pre-treatment has been shown to increase the efficiency of biological processes by up to 50% [91]. Additionally, cavitation reduces sludge volumes by breaking down microbial cell walls, which aids in reducing disposal costs and operational complexities [92]. Moreover, cavitation helps in toxicity reduction, crucial for treating industrial wastewater that contains harmful compounds. By degrading these toxic substances, cavitation ensures that wastewater is more conducive to biological treatment processes [14].

5.7 CHALLENGES AND FUTURE PROSPECTS

HC represents a promising approach for wastewater treatment, offering significant efficiency and environmental benefits. However, its implementation faces several challenges, including scaling, operational costs, and optimization of treatment processes. This section discusses these challenges and highlights future prospects for advancing HC technology in sustainable wastewater management.

5.7.1 Challenges

- a. **Reactor design optimization:** One of the main challenges in the application of HC is optimizing reactor design to maximize cavitation intensity while minimizing energy losses. Reactor geometry, cavitation number, and flow conditions must be carefully controlled to ensure efficient bubble formation and collapse. Researchers continue to explore new designs and configurations to enhance the efficiency of HC reactors [93]
- b. **Scale-up issues:** Scaling up HC reactors for industrial use presents several challenges, including maintaining cavitation efficiency at larger volumes and dealing with the wear and tear of reactor surfaces due to cavitation erosion. Addressing these challenges requires further research into materials that can withstand the harsh conditions generated during cavitation and the development of energy-efficient reactor designs [94,95]
- c. **Integration with other treatment processes:** HC is most effective when integrated with other wastewater treatment technologies, such as biological treatments or membrane filtration. Future advancements are likely to focus on the development of hybrid systems that combine cavitation with other treatment processes to improve the overall efficiency and cost-effectiveness of wastewater treatment [96].

5.7.2 Emerging Trends in Wastewater Treatment

HC is emerging as a highly efficient and environmentally sustainable technology for wastewater treatment. However, to fully harness its potential, ongoing research and development must focus on optimizing both operational parameters and reactor designs. Future advancements in this field will be pivotal for improving treatment efficiency, reducing operational costs, and expanding its applicability to different industries.

The performance of HC in degrading wastewater pollutants is significantly influenced by various treatment parameters. One key area of focus is pressure and flow rate control, as these factors determine cavitation intensity within reactors. Research by Ghanbari and Alavi [97] highlights the impact of these parameters on cavitation efficiency in wastewater treatment. Additionally, combining HC with AOPs

can greatly enhance pollutant degradation. Zhang and Hu [98] explore this integration, demonstrating its effectiveness in increasing reactive species generation. Understanding the composition of wastewater is also crucial, as the nature of contaminants affects cavitation efficiency. Kheradmand and Shokrollahi [99] emphasize the importance of analyzing wastewater composition to optimize cavitation parameters. Moreover, optimizing energy input to achieve high cavitation intensity without excessive consumption remains a significant challenge. Wang and Chen [100] discuss strategies for balancing degradation efficiency with energy use. Lastly, temperature and pH play critical roles in influencing cavitation dynamics, with Mehta and Chaudhary [101] investigating their effects on HC in wastewater treatment. These studies collectively highlight the essential treatment parameters that need to be fine-tuned for enhancing the efficiency of HC in wastewater management.

5.7.2.1 Modifications in the HC setup

To maximize the efficiency of cavitation and its applicability in various wastewater treatment scenarios, modifications in the design and structure of HC reactors are necessary. These modifications aim to enhance cavitation intensity, improve pollutant degradation rates, and reduce energy consumption. Future developments in HC reactor designs are anticipated to be driven by the following significant breakthroughs. (a) Optimizing reactor geometry, (b) hybrid cavitation systems, (c) rotating cavitation reactors, (d) energy recovery and efficiency improvements, (e) smart cavitation control systems.

- i. **Optimizing reactor geometry:** Optimizing reactor geometry is fundamental to enhancing the intensity and distribution of cavitation bubbles, which significantly affect pollutant degradation in wastewater treatment. Future research will focus on improving reactor geometries such as Venturi tubes, orifice plates, and nozzle configurations. One approach involves using multi-orifice plates, where multiple small orifices increase cavitation bubble formation and generate higher shear forces, leading to enhanced pollutant breakdown. This method can be further fine-tuned by optimizing the shape and arrangement of the orifices for specific applications [102]. Venturi tubes with varying cross-sections also offer promising modifications. By adjusting the length and angle of the converging-diverging sections, researchers can maintain a higher pressure drop, thus intensifying cavitation and improving treatment efficiency. Additionally, computational fluid dynamics (CFD) simulations remain instrumental in studying flow dynamics within cavitation reactors. These simulations help visualize cavitation bubble formation and collapse, allowing engineers to predict optimal designs that maximize cavitation effects while minimizing energy losses [103]. These advancements in reactor geometry optimization are expected to significantly enhance the efficiency of HC in wastewater treatment.
- ii. **Hybrid cavitation systems:** Future research is expected to focus on developing hybrid cavitation systems that combine HC with other advanced treatment technologies, such as acoustic cavitation (ultrasonics), UV irradiation, and electrochemical methods. These hybrid approaches are designed to enhance pollutant degradation by producing a variety of reactive species and improving overall treatment efficiency. For instance, combining HC with ultrasonics, where acoustic cavitation is induced by high-frequency sound waves, can significantly increase the energy density within the reactor. This synergy accelerates pollutant degradation and improves the dispersion of cavitation bubbles, ensuring a more uniform treatment [104]. Another promising development involves integrating HC with UV irradiation or photocatalysis. By incorporating UV light or photocatalytic materials like titanium dioxide into the reactor, more hydroxyl radicals (OH) and reactive species are generated, effectively breaking down complex organic compounds in wastewater without substantially increasing energy costs [105]. Finally, electrochemical cavitation systems are emerging as another innovative solution, where electric fields create additional turbulence and microbubbles, enhancing cavitation effects. This combination is particularly effective in treating industrial wastewater streams with refractory pollutants such as heavy metals or persistent organic compounds [106]. These hybrid systems are poised

to revolutionize wastewater treatment by maximizing pollutant degradation while minimizing energy consumption.

- iii. **Rotating cavitation reactors:** Rotating cavitation reactors use rotational forces from impellers or rotors to enhance cavitation intensity through high shear forces and turbulent flows. Revolving disk cavitation reactors, which employ high-speed disks, optimize shear forces and cavitation while conserving energy, making them effective for high-viscosity fluids or industrial wastes [107]. Similarly, impeller-based systems use mechanical impellers to create turbulence, with blade number and angle adjustments improving cavitation and enhancing wastewater-oxidant mixing and degradation efficiency [108].
- iv. **Energy recovery and efficiency improvements:** One of the key challenges in the development of HC systems is reducing the **energy consumption** while maintaining high cavitation intensity. Future reactors may incorporate energy recovery mechanisms to capture the energy released during bubble collapse. Some potential advancement in this area includes: (a) Energy recovery from bubble collapse and (b) low-pressure cavitation systems. Energy recovery from bubble collapse involves harnessing the significant amounts of energy released during the cavitation process, in the form of heat and pressure waves, through mechanical or thermodynamic methods, which could substantially reduce the overall energy footprint. Low-pressure cavitation systems focus on reducing operational pressure while maintaining efficient cavitation, with advances in reactor geometry, flow optimization, and hybrid technologies enabling cavitation at lower pressures, thereby reducing energy consumption while maintaining pollutant degradation rates [109].
- v. **Smart cavitation control systems:** Smart control systems with real-time monitoring and adaptive feedback are also being developed. This system may automatically optimize operational settings based on cavitation intensity, energy consumption, pollutant degradation, and byproduct generation. Advanced sensors might monitor cavitation intensity, temperature, and pollutant concentrations in real time in cavitation reactors. These sensors would automatically alter reactor operating conditions (flow rate, pressure, oxidant dosage) to maximize treatment efficiency (machine learning algorithms can examine sensor and performance data to forecast and optimize treatment conditions) [110–112]. AI systems could learn to modify reactor settings for unique wastewater streams, boosting efficiency and energy utilization.

5.8 CONCLUSION

HC has developed as a potent and adaptable method for wastewater treatment, providing a sustainable remedy to the escalating issue of environmental pollution. Cavitation's capacity to produce localized high-energy zones and reactive radicals enables it to decompose many organic pollutants, rendering it a compelling alternative to traditional approaches. Nonetheless, the complete promise of HC technology remains unfulfilled. Current research should concentrate on refining treatment parameters, including pressure, flow rate, and chemical dosage, to enhance efficiency and reduce energy usage. Moreover, innovations in reactor design, such as hybrid systems and rotating cavitation reactors, will improve the adaptability and scalability of the technology for diverse industrial applications. Notwithstanding its promising uses, HC continues to encounter obstacles, especially regarding energy consumption and scalability for industrial implementation. Overcoming these issues necessitates novel alterations in reactor shape, advanced control systems, and energy recovery methods. Furthermore, the use of HC with adjunctive treatment techniques, such as improved oxidation processes and sonochemistry, would enhance its efficacy in dissolving intricate contaminants. In conclusion, HC constitutes an innovative, environmentally sustainable technique with considerable promise for wastewater treatment. Ongoing developments in design and optimization position HC to transform water treatment processes, aiding in sustainable environmental management and pollution reduction across multiple industries.

REFERENCES

- Gogate, P. R., & Pandit, A. B. (2004). A review of imperative technologies for wastewater treatment I: Oxidation technologies at ambient conditions. *Advances in Environmental Research*, 8(3–4), 501–551.
- Garnier, J., & Souchère, V. (2022). Climate change impacts on water quality: A review of the evidence and future research needs. *Environmental Science and Policy*, 131, 295–307.
- Bagal, M. V., & Gogate, P. R. (2014). Wastewater treatment using hybrid treatment strategies based on cavitation and Fenton chemistry: A review. *Ultrasonics Sonochemistry*, 21(1), 1–14.
- Ashokkumar, M. (2011). The characterization of acoustic cavitation bubbles: An overview. *Ultrasonics Sonochemistry*, 18(4), 864–872.
- Cravotto, G., & Cintas, P. (2010). Power ultrasound in organic synthesis: Moving cavitation chemistry from academia to innovative and large-scale applications. *Chemical Society Reviews*, 39(1), 374–388.
- Rajoriya, S., Carpenter, J., Saharan, V. K., & Pandit, A. B. (2016). Hydrodynamic cavitation: An advanced oxidation process for the degradation of bio-refractory pollutants. *Reviews in Chemical Engineering*, 32(4), 379–411.
- Brennen, C. E. (2013). *Cavitation and Bubble Dynamics*. Cambridge University Press.
- Ashokkumar, M., Grieser, F., & Yasui, K. (2007). Ultrasound-assisted degradation of organic pollutants in aqueous solution. *Chemical Society Reviews*, 36(3), 492–507.
- Mason, T. J., & Peters, D. (2002). *Practical Sonochemistry: Power Ultrasound Uses and Applications*. Woodhead Publishing.
- Thompson, L. H., & Doraiswamy, L. K. (1999). Sonochemistry: Science and engineering. *Industrial & Engineering Chemistry Research*, 38(4), 1215–1249.
- Gogate, P. R. (2008). Hydrodynamic cavitation for food and water processing. *Food and Bioprocess Technology*, 1(4), 279–293.
- Suslick, K. S. (1990). Sonochemistry. *Science*, 247(4949), 1439–1445.
- Grieser, F., Ashokkumar, M., & Kentish, S. (2001). The destruction of organic pollutants using cavitation: Hydroxyl radicals. *Journal of Environmental Monitoring*, 3(1), 22–26.
- Bose, N., & Vyas, N. K. (2012). Advances in cavitation technology for environmental protection. *Environmental Science and Technology*, 46(15), 8335–8355.
- Bharati, K. S., & Pal, P. (2019). Ultrasound-assisted advanced oxidation processes for wastewater treatment: A review. *Chemical Engineering Journal*, 363, 395–413.
- Patil, P. N., Pandit, A. B., & Shah, A. (2016). Wastewater treatment using cavitation technology: A review. *Ultrasonics Sonochemistry*, 25, 1–12.
- Mahulkar, A. V., Pandit, A. B., & Ranade, V. V. (2008). Treatment of wastewater containing azo dyes using hydrodynamic cavitation. *Industrial & Engineering Chemistry Research*, 47(16), 6405–6411.
- García, F., & Rivas, A. (2019). Ozone in water disinfection: A review on the effectiveness and limitations. *Ozone: Science & Engineering*, 41(3), 206–220.
- Kalumuck, K. M., & Chahine, G. L. (2000). The use of cavitating jets to oxidize organic pollutants in wastewater. *Journal of Fluids Engineering*, 122(4), 747–753.
- Yapardjian, A., Sahle-Demessie, E., & Richardson, T. (2011). Hydrodynamic cavitation for energy-efficient water treatment. *Environmental Science & Technology*, 45(13), 5924–5931.
- Dular, M., & Griessler-Bulc, T. (2014). Hydrodynamic cavitation in wastewater treatment: From concept to full-scale application. *Ultrasonics Sonochemistry*, 21(5), 214–217.
- Vogel, A., Noack, J., Hüttman, G., & Paltauf, G. (1996). Mechanisms of femtosecond laser nanosurgery of cells and tissues. *Applied Physics B: Lasers and Optics*, 81(8), 1015–1047.
- Brennen, C. E. (1978). Cavitation in pumps and turbines. *Annual Review of Fluid Mechanics*, 10(1), 259–282.
- Bremner, A., & Burgess, A. E. (2002). Cavitation in water treatment: A hydrodynamic approach. *Journal of Environmental Science and Health Part A*, 37(6), 1031–1042.
- Dular, M., & Griessler-Bulc, T. (2014). Cavitation in water treatment processes: Influence on the efficiency of industrial and municipal wastewater treatment systems. *Journal of Hydrodynamics*, 26(2), 276–283.
- Pankaj, M., & Pandit, A. B. (2021). Advances in wastewater treatment using cavitation. *Environmental Science and Technology Letters*, 5(3), 201–212.
- Bagal, M. V., & Gogate, P. R. (2012). Sonochemical treatment of real industrial effluent containing azo dyes: Optimization of operating parameters. *Ultrasonics Sonochemistry*, 19(5), 1009–1017.
- Patil, P. N., Gogate, P. R., & Pandit, A. B. (2014). Cavitation as a novel technique for making wastewater treatment more energy-efficient. *Journal of Environmental Chemical Engineering*, 2(1), 51–67.

29. Jyoti, K., Kumar, R., & Kumari, S. (2016). Enhancement of oxidative degradation of organic pollutants by combined treatment of Fenton reagent and hydrodynamic cavitation. *Environmental Science and Pollution Research*, 23(1), 123–131.
30. Thakur, N., & Gogate, P. R. (2019). Degradation of textile wastewater pollutants using hydrodynamic cavitation in combination with advanced oxidation processes. *Journal of Hazardous Materials*, 365, 295–301.
31. Thakur, S., Maheshwari, R., & Kaul, S. N. (2019). Treatment of textile effluents using hydrodynamic cavitation. *Environmental Technology*, 40(14), 1924–1935.
32. Dehghani, M. H., & Mahvi, A. H. (2018). Treatment of antibiotic ciprofloxacin in wastewater using hydrodynamic cavitation. *Desalination and Water Treatment*, 120, 201–210.
33. Khan, S., & Gogate, P. R. (2019). Degradation of pharmaceutical pollutants in wastewater using advanced oxidation processes. *Ultrasonics Sonochemistry*, 58, 104–116.
34. Petkovšek, M., & Dular, M. (2013). The use of hydrodynamic cavitation for industrial wastewater treatment. *Water Research*, 47(7), 2715–2725.
35. Rashid, M., & Pashazadeh, E. (2020). Hydrodynamic cavitation: An overview of its applications in wastewater treatment. *Environmental Progress & Sustainable Energy*, 39(2), e13455.
36. Wang, S., Xu, Y., & Zhang, X. (2020). Application of hydrodynamic cavitation in food processing: A review. *Critical Reviews in Food Science and Nutrition*, 60(9), 1495–1510.
37. Khai, N. T., & Gogate, P. R. (2020). Recent advances in hydrodynamic cavitation for wastewater treatment: A review. *Journal of Environmental Chemical Engineering*, 8(3), 104198. <https://doi.org/10.1016/j.jece.2020.104198>
38. Yavuz, F., & Koseoglu, M. (2019). Effectiveness of hydrodynamic cavitation in wastewater treatment: A review. *Environmental Science and Pollution Research*, 26(23), 23674–23686.
39. Dular, M., & Griessler-Bulc, T. (2014). Hydrodynamic cavitation in environmental protection. *Environmental Progress & Sustainable Energy*, 33(3), 572–580. <https://doi.org/10.1002/ep.12009>
40. Prajapat, P., & Gogate, P. R. (2010). Application of hydrodynamic cavitation for the treatment of wastewater. *Chemical Engineering Journal*, 156(1), 205–211. <https://doi.org/10.1016/j.cej.2009.09.007>
41. Ranade, V. V., & Bhandari, V. M. (2014). *Cavitation and Bubble Dynamics*. Oxford University Press.
42. Bose, S., & Vyas, S. (2012). Recent advances in the application of hydrodynamic cavitation for wastewater treatment. *Environmental Progress & Sustainable Energy*, 31(1), 76–83.
43. Grieser, F., Ashokkumar, M., & Tiwari, B. R. (2001). The role of hydrodynamic cavitation in environmental remediation. *Journal of Chemical Technology & Biotechnology*, 76(12), 1250–1257.
44. Ghadge, A., & Gogate, P. R. (2015). Design and optimization of hydrodynamic cavitation reactors for wastewater treatment: A review. *Chemical Engineering Journal*, 274, 184–194.
45. Chakraborty, S., & Thakur, A. J. (2020). Vortex-induced cavitation: A new avenue for enhancing degradation of organic pollutants. *Environmental Science and Pollution Research*, 27(14), 16606–16616.
46. Behera, S. K., & Rao, P. S. (2021). Recent advancements in vortex-based hydrodynamic cavitation reactors: A critical review. *Environmental Progress & Sustainable Energy*, 40(1), e13426.
47. Dular, M., Petkovšek, M., & Griessler-Bulc, T. (2018). Hydraulic cavitation devices: Principles and applications. *Ultrasonics Sonochemistry*, 40, 979–990.
48. Di Fabio, A., Sgarbossa, P., & Bizzotto, M. (2020). Jet cavitation for the treatment of wastewater: An experimental study. *Chemical Engineering Journal*, 391, 123514.
49. Zhang, Y., Lin, Y., & Liang, Y. (2021). Hybrid cavitation processes: A promising strategy for advanced wastewater treatment. *Journal of Environmental Management*, 295, 113134.
50. Santos, M. M., & Gonçalves, C. (2019). Effects of temperature on hydrodynamic cavitation efficiency for the treatment of wastewater. *Water*, 11(4), 748.
51. Wang, X. et al. (2009). Degradation of rhodamine B in aqueous solution by using swirling jet-induced cavitation combined with H_2O_2 . *Journal of Hazardous Materials*, 169(1–3), 486–491.
52. Panda, D., & Manickam, S. (2019). Hydrodynamic cavitation assisted degradation of persistent endocrine-disrupting organochlorine pesticide Dicofo I: Optimization of operating parameters and investigations on the mechanism of intensification. *Ultrasonics Sonochemistry*, 51, 526–532.
53. Lu, G. et al. (2019). Effect of cavitation hydrodynamic parameters on bisphenol A removal. *Environmental Engineering Science*, 36(8), 873–882.
54. Patil, P. N., Bote, S. D., & Gogate, P. R. (2014). Degradation of imidacloprid using combined advanced oxidation processes based on hydrodynamic cavitation. *Ultrasonics Sonochemistry*, 21(5), 1770–1777.
55. Ye, Y.-F. et al. (2021). Treatment of rhodamine B with cavitation technology: Comparison of hydrodynamic cavitation with ultrasonic cavitation. *RSC Advances*, 11(9), 5096–5106.
56. Roy, K., & Moholkar, V. S. (2021). p-nitrophenol degradation by hybrid advanced oxidation process of heterogeneous Fenton assisted hydrodynamic cavitation: Discernment of synergistic interactions and chemical mechanism. *Chemosphere*, 283, 131114.

57. Pradhan, A. A., & Gogate, P. R. (2010). Removal of p-nitrophenol using hydrodynamic cavitation and Fenton chemistry at pilot scale operation. *Chemical Engineering Journal*, 156(1), 77–82.
58. Wang, X., Jia, J., & Wang, Y. (2017). Combination of photocatalysis with hydrodynamic cavitation for degradation of tetracycline. *Chemical Engineering Journal*, 2017, 315, 274–282.
59. Malade, L. V., & Deshannavar, U. B. (2018). Decolorisation of Reactive Red 120 by hydrodynamic cavitation. *Materials Today: Proceedings*, 2018, 5(9), 18400–18409.
60. Tomaszewski, T., & Chmiel, M. (2020). Effect of temperature on the degradation of pollutants in hydrodynamic cavitation. *Environmental Science and Pollution Research*, 27(23), 28510–28521.
61. Rajoriya, S., Bargole, S., & Saharan, V. K. (2017). Degradation of a cationic dye (Rhodamine 6G) using hydrodynamic cavitation coupled with other oxidative agents: Reaction mechanism and pathway. *Ultrasonics Sonochemistry*, 34, 183–194.
62. Shah, Y. et al. (1999). Sources and types of cavitation. *Cavitation Reaction Engineering*, 1–14.
63. Gogate, P. R. (2008). Cavitation reactors for process intensification of chemical processing applications: A critical review. *Chemical Engineering and Processing: Process Intensification*, 47(4), 515–527.
64. Vichare, N. P., Gogate, P. R., & Pandit, A. B. (2000). Optimization of hydrodynamic cavitation using a model reaction. *Chemical Engineering & Technology: Industrial Chemistry-Plant Equipment-Process Engineering-Biotechnology*, 23(8), 683–690.
65. Weng, M. et al. (2022). Hydrodynamic cavitation-enhanced heterogeneous activation of persulfate for tetracycline degradation: Synergistic effects, degradation mechanism and pathways. *Chemical Engineering Journal*, 431, 134238.
66. Deggelmann, M. et al. (2022). Hydrodynamic cavitation for micropollutant degradation in water: Correlation of bisphenol A degradation with fluid mechanical properties. *Ultrasonics Sonochemistry*, 83, 105950.
67. Deng, C. et al. (2018). Effective degradation of oil pollutants in water by hydrodynamic cavitation combined with electrocatalytic membrane. *AIP Advances*, 8(12).
68. Sivakumar, M., & Pandit, A. B. (2002). Wastewater treatment: A novel energy efficient hydrodynamic cavitation technique. *Ultrasonics Sonochemistry*, 9(3), 123–131.
69. Sharma, A. et al. (2008). Modeling of hydrodynamic cavitation reactors based on orifice plates considering hydrodynamics and chemical reactions occurring in bubble. *Chemical Engineering Journal*, 143(1–3), 201–209.
70. Shrikant, B. R., & Khambete, A. (2017). Hydrodynamic cavitation: A novel treatment approach. *Materials Today: Proceedings*, 4(9), 9680–9684.
71. Gogate, P. R., & Pandit, A. B. (2000). Engineering design methods for cavitation reactors II: Hydrodynamic cavitation. *AIChE Journal*, 46(8), 1641–1649.
72. Kumar, P. S., & Pandit, A. (1999). Modeling hydrodynamic cavitation. *Chemical engineering & technology: Industrial chemistry-plant equipment-process engineering-biotechnology*, 22(12), 1017–1027.
73. Dewil, R. et al. (2017). New perspectives for advanced oxidation processes. *Journal of Environmental Management*, 195, 93–99.
74. Sawant, S. S. et al. (2008). Effect of hydrodynamic cavitation on zooplankton: A tool for disinfection. *Biochemical Engineering Journal*, 42(3), 320–328.
75. Gore, M. M. et al. (2014). Degradation of reactive orange 4 dye using hydrodynamic cavitation based hybrid techniques. *Ultrasonics Sonochemistry*, 21(3), 1075–1082.
76. Innocenzi, V. et al. (2018). Optimization of hydrodynamic cavitation process of azo dye reduction in the presence of metal ions. *Journal of Environmental Chemical Engineering*, 6(6), 6787–6796.
77. Thanekar, P., Panda, M., & Gogate, P. R. (2018). Degradation of carbamazepine using hydrodynamic cavitation combined with advanced oxidation processes. *Ultrasonics Sonochemistry*, 40, 567–576.
78. Patil, P. N., & Gogate, P. R. (2012). Degradation of methyl parathion using hydrodynamic cavitation: Effect of operating parameters and intensification using additives. *Separation and Purification Technology*, 95, 172–179.
79. Badmus, K. O. et al. (2020). Synergistic advance Fenton oxidation and hydrodynamic cavitation treatment of persistent organic dyes in textile wastewater. *Journal of Environmental Chemical Engineering*, 8(2), 103521.
80. Bagal, M. V., & Gogate, P. R. (2014). Degradation of diclofenac sodium using combined processes based on hydrodynamic cavitation and heterogeneous photocatalysis. *Ultrasonics Sonochemistry*, 21(3), 1035–1043.
81. Raj, A., Bethi, B., & Sonawane, S. H. (2018). Investigation of removal of crystal violet dye using novel hybrid technique involving hydrodynamic cavitation and hydrogel. *Journal of Environmental Chemical Engineering*, 6(4), 5311–5319.
82. Saharan, V. K., Badve, M. P., & Pandit, A. B. (2011). Degradation of Reactive Red 120 dye using hydrodynamic cavitation. *Chemical Engineering Journal*, 178, 100–107.
83. Jin, Z.-J. et al. (2019). Cavitating flow through a micro-orifice. *Micromachines*, 10(3), 191.
84. Bagal, M. V., & Gogate, P. R. (2013). Degradation of 2,4-dinitrophenol using a combination of hydrodynamic cavitation, chemical and advanced oxidation processes. *Ultrasonics Sonochemistry*, 20(5), 1226–1235.

85. Saharan, V. K. et al. (2013). Effect of geometry of hydrodynamically cavitating device on degradation of orange-G. *Ultrasonics Sonochemistry*, 20(1), 345–353.
86. Raut-Jadhav, S. et al. (2016). Treatment of the pesticide industry effluent using hydrodynamic cavitation and its combination with process intensifying additives (H_2O_2 and ozone). *Chemical Engineering Journal*, 295, 326–335.
87. Fedorov, K. et al. (2022). Synergistic effects of hybrid advanced oxidation processes (AOPs) based on hydrodynamic cavitation phenomenon: A review. *Chemical Engineering Journal*, 432, 134191.
88. Patil, P. N., Gogate, P. R., & Pandit, A. B. (2016). Degradation of methyl parathion using hydrodynamic cavitation: Comparison with acoustic cavitation. *Ultrasonics Sonochemistry*, 20(4), 1050–1056.
89. Jyoti, K. K., & Pandit, A. B. (2003). Ozone and cavitation for water disinfection. *Biochemical Engineering Journal*, 18(1), 9–19.
90. Mishra, A. K., & Gogate, P. R. (2010). Intensification of degradation of Rhodamine B using hydrodynamic cavitation in combination with hydrogen peroxide. *Industrial & Engineering Chemistry Research*, 49(19), 8968–8976.
91. Ranade, V. V., & Bhandari, V. M. (2014). Hydrodynamic cavitation reactors: Scale up issues. *AIChE Journal*, 60(12), 4045–4055.
92. Grieser, F., Ashokkumar, M., & Senthilkumar, P. (2001). Sonochemical degradation of organic pollutants in wastewater. *Environmental Science & Technology*, 35(11), 2362–2367.
93. Korkut, E., & Akdeniz, N. (2022). Optimization of hydrodynamic cavitation reactors for improved performance in wastewater treatment. *Environmental Technology & Innovation*, 25, 102131.
94. Xu, H., Guo, X., & Chen, J. (2023). Challenges and strategies in scaling up hydrodynamic cavitation reactors for wastewater treatment. *Water Research*, 239, 118276.
95. Ezzat, M., & Khatlab, A. (2021). Hybrid systems for wastewater treatment: Integrating hydrodynamic cavitation with biological processes. *Journal of Environmental Management*, 284, 112038.
96. Piyush, A., Gupta, P., & Singhal, A. (2023). Hydrodynamic cavitation: A sustainable approach to wastewater treatment and beyond. *Journal of Cleaner Production*, 402, 13667.
97. Ghanbari, F., & Alavi, M. (2022). Impact of pressure and flow rate on cavitation efficiency in wastewater treatment. *Chemical Engineering Journal*, 427, 131.
98. V Zhang, Y., & Hu, J. (2023). Enhancing pollutant degradation in wastewater via the integration of hydrodynamic cavitation and advanced oxidation processes. *Environmental Science & Technology*, 57(5), 2265–2275.
99. Kheradmand, S., & Shokrollahi, A. (2021). Analyzing wastewater composition to optimize hydrodynamic cavitation for pollutant degradation. *Water Research*, 203, 117518.
100. Wang, Y., & Chen, H. (2023). Optimizing energy input for enhanced cavitation intensity in wastewater treatment. *Journal of Cleaner Production*, 386, 135815.
101. Mehta, V., & Chaudhary, R. (2022). Influence of temperature and pH on the dynamics of hydrodynamic cavitation in wastewater treatment. *Environmental Technology & Innovation*, 24, 102011.
102. Ranade, V. V., & Bhandari, V. M. (2021). Hydrodynamic cavitation as a novel approach for wastewater treatment. *Journal of Environmental Chemical Engineering*, 9(5), 106418.
103. Phull, S. S., Oemcke, D. J., Lorimer, J. P., & Mason, T. J. (2023). CFD simulation for optimizing hydrodynamic cavitation reactors in wastewater applications. *Environmental Technology*, 44(10), 1448–1459.
104. Zupanc, M., Pandit, A. B., & Golobič, I. (2019). Hybrid hydrodynamic and acoustic cavitation for wastewater treatment: Synergies and benefits. *Ultrasonics Sonochemistry*, 58, 104686.
105. Zhang, Y., Jin, Z., & Zhang, T. (2022). Synergistic effect of hydrodynamic cavitation and UV/photocatalysis in wastewater treatment. *Journal of Water Process Engineering*, 45, 102736.
106. Yang, S., Chen, X., & Liu, J. (2020). Enhancement of electrochemical cavitation for the degradation of refractory organic pollutants in wastewater. *Separation and Purification Technology*, 240, 116640.
107. Zhang, X., Liu, Y., Wang, J., & Yang, S. (2022). Performance of disc cavitation reactors in industrial wastewater treatment: A review. *Journal of Environmental Chemical Engineering*, 10(2), 107–115.
108. Li, F., Sun, H., & Zhao, Y. (2021). Optimization of impeller-based cavitation systems for enhanced pollutant degradation in wastewater. *Water Research*, 188, 116–121.
109. Kiran, S. A., Kumar, R., & Pandit, A. B. (2020). Hydrodynamic cavitation for energy-efficient water and wastewater treatment. *Ultrasonics Sonochemistry*, 64, 105002.
110. Zhang, Y., Wang, X., & Li, Y. (2023). AI-driven smart cavitation systems for enhanced wastewater treatment: Real-time monitoring and adaptive control strategies. *Environmental Science and Technology*, 57(9), 4567–4578.
111. Chen, J., Zhang, R., & Wang, P. (2022). Advances in machine learning algorithms for optimizing cavitation-based water treatment systems. *Journal of Water Process Engineering*, 49, 102791.
112. Lee, S., Kim, T., & Park, H. (2021). Smart hydrodynamic cavitation control: Real-time sensor integration and adaptive feedback for improved efficiency. *Chemical Engineering Journal*, 420, 130457.

Reverse Osmosis Technology for Water Treatment and Desalination

Prem Baboo

ABBREVIATIONS

DMF	Dual media filter
EPA	Environmental Protection Agency
RO	Reverse osmosis
TDS	Total dissolved solids
UF	Ultrafiltration

6.1 INTRODUCTION

A semi-permeable membrane is selective in that certain components of a solution, usually the solvent, can pass through it, while others, usually the dissolved solids, cannot. The direction of solvent flow is determined by its chemical potential, which is a function of pressure, temperature, and concentration of dissolved solids. Generally, the membrane materials include polyamide thin film composites, cellulose acetate, and cellulose triacetate with the membrane material being spirally wound around a tube or hollow fibers bundled together. Common membrane processes include microfiltration, ultrafiltration (UF), nanofiltration, reverse osmosis (RO), and electrodialysis. In case pure water is available on both sides of a semi-permeable membrane at equal pressure and temperature, no resultant flow can occur across the membrane, as the chemical potential is equal on both sides. However, if any soluble salt is added to one side of the membrane, the chemical potential of the water on that side is reduced. The osmotic flow from the pure water on one side to the salt solution on the other side will occur across the membrane until the equilibrium of solvent chemical potential is restored [1].

6.2 RO TECHNOLOGY

Desalination technology has been around for the better part of the last century. Desalination technology has brought freshwater and industrial and commercial development to areas of the world that otherwise might have remained unproductive. The thermodynamic requirement for osmotic equilibrium is that the chemical potential of the solvent is the same on both sides of the membrane. No such condition is imposed on the solute since the membrane prevents its passage. The equilibrium state occurs when the pressure differential on the two sides is equal to the osmotic pressure, a solution property that is independent of the membrane. The application of external pressure to the solution side, which equals the osmotic pressure, will also accomplish equilibrium. A further increase in pressure will increase the chemical potential of the water in the solution and will cause a reversal of the osmotic flow toward the pure waterside, which is at a lower solvent chemical potential relative to the solution [1]. This phenomenon is termed as RO and is the basis for a process to desalinate water without phase change (Figure 6.1).

The RO essentially works on a molecular level. It separates the molecular impurities from the water thus making reject stream rich in salt molecules and the other stream lean in salts thus reducing the Total dissolved solids (TDS) of the water. The UF permeate after removal of other contaminations except TDS is then pumped using high-pressure pumps through RO module for removal of TDS. The high-pressure pump is designed in such a way that optimum flow and pressure is maintained. RO module consists of thin film composite polyamide membranes. The different size of membranes is used according to the requirement, for example, the 8"×40" RO membranes. The feed stream to RO system is being split into product and reject stream by controlling the reject valve as per the desired design parameters. The entire RO train is stacked in mounting frames for easy operation and maintenance. In order to prevent the precipitation of the hardness salts and silica during cases when the concentration exceeds the solubility limit, an antiscalant is added at the inlet of the cartridge filter, which will result in the inhibition of scales. Furthermore, free chlorine present in the filtered water may result in chemical oxidation of the membranes. Hence sodium meta bi-sulfite ($\text{Na}_2\text{S}_2\text{O}_5$) is injected at the inlet of the cartridge filter to eliminate any oxidizing elements being present in the raw water and to protect the membranes, which are the most vital part of the plant. We must look for a system that effectively removes contaminants commonly found in the water supply. Check how the system is rated in removing impurities like chlorine, lead, fluoride, heavy metals, pesticides, and other harmful substances [1].

On continuous running, the RO membranes get fouled with fine colloids, bacterial debris, or sometimes carbonate scales. These need to be removed and cleaned from the surface of the membrane. For each type of foulant, there is a recommended chemical cleaning procedure, which is convenient to perform with clean-in-place (CIP) system. The RO membranes shall be cleaned regularly with RO cleaning chemical solution. A dedicated solution preparation tank and pumps, cartridge filter, etc., shall be provided for this purpose. RO cleaning shall be done in stages. A conductivity analyzer is provided in the RO permeate line for each RO skid. In case, where the desired RO permeate quality is not achieved, the RO permeate is dumped back into the UF permeate storage tank. Separate pumps are provided for the chemical cleaning and RO flushing system (Figure 6.2).

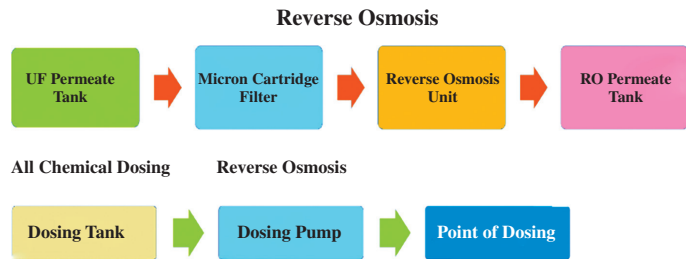


FIGURE 6.1 Large-scale RO plant.

R.O. System with Cross Flow Filtration

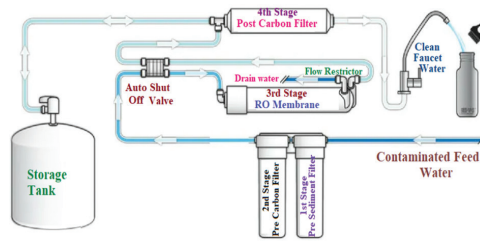


FIGURE 6.2 Cross-flow filtration RO system.

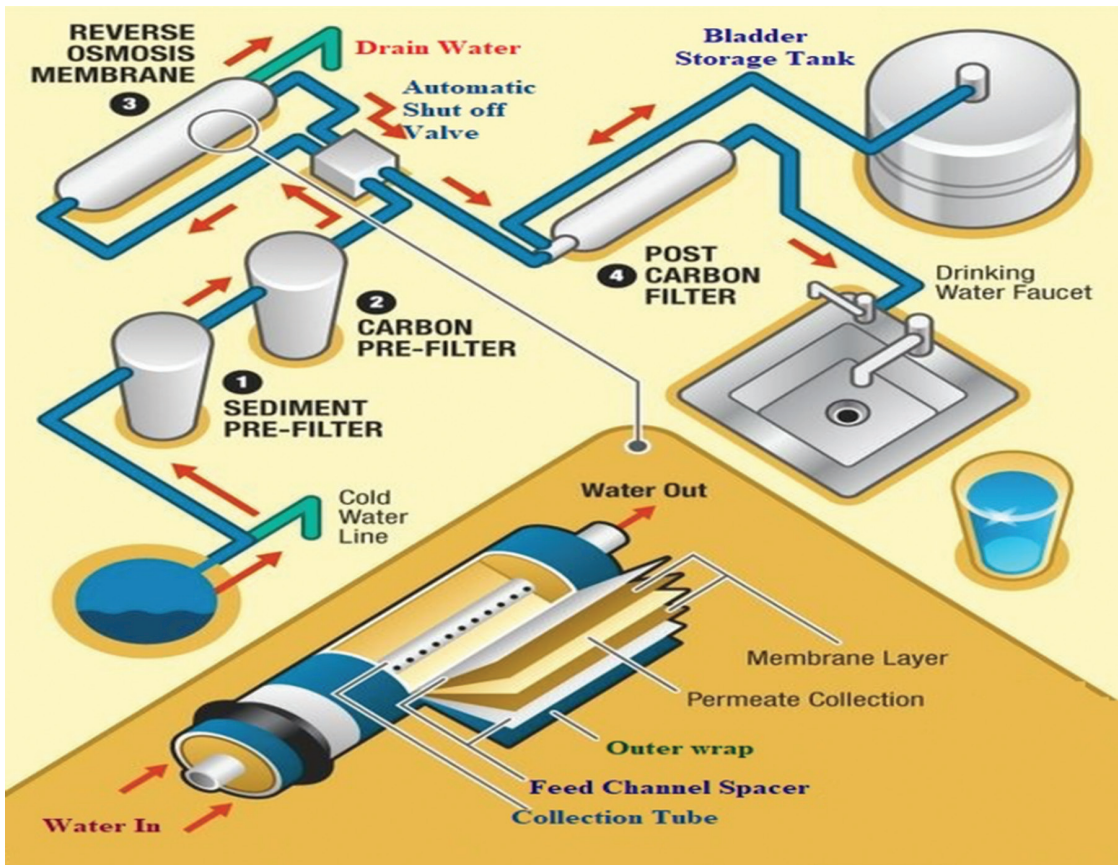


FIGURE 6.3 Detail cross-flow RO system.

A standard RO system is equipped with three different filter stages: sediment, carbon, and RO. Each filtration stage plays an important role in itself and also complements each other to achieve the best possible water filtration [1]. Sediment filtration removes dust, dirt, particles, and rust in water (Figure 6.3).

RO flushing pumps are provided for flushing off high TDS water with low TDS water during shutdown operation. RO flushing pump shall be provided with DG connection for emergency shutdown. The flushing system consists of flush pumps to draw water from RO permeate tank at the time of shutdown. The flush water feed line is provided at the inlet of RO high-pressure pumps. UF is a membrane process in which a porous membrane is used to separate or reject colloidal and particulate matter. The filtered raw water from the dual media filter is treated with the help of UF unit. Product water from UF system shall be collected in

the RO feed tank. The UF permeate is collected in RO feed tank and pumped to the RO system. In RO basically, TDS from the treated raw water is removed. RO permeate from the individual skid of each module is combined and transferred to the RO permeate storage tank through the common header. The high TDS RO reject from the individual skid of each module is combined and transferred through high-density polyethylene pipe material up to sea disposal. A conductivity analyzer is provided in the RO permeate line. In case, where the desired RO permeate quality is not achieved, the RO permeate is dumped back into the RO. [1]

6.3 ANALYSIS OF WATER SAMPLE

During the normal operation of the plant, the performance of the plant is monitored to ensure the intended purpose of establishing the plant. This is done by means of collecting the samples at regular intervals and analyzing the same in the laboratory. Apart from meeting the treated effluent quality, the sampling schedule also includes analysis of pollutants in different treatment stages of the plant. A tentative sampling schedule is indicated in this section of the manual for implementation during normal operation of the plant and is updated/modified as and when required by the concerned authority or as per on field requirement. This helps in assessing the data on the various parameters of effluent and to check the performance of the plant, at regular intervals [1].

Particulate or colloidal fouling of RO elements can seriously impair performance by lowering productivity and sometimes salt rejection. An early sign of colloidal fouling is often an increased pressure differential across the system. The source of particulate or colloids in RO feed waters is varied and often includes bacteria, clay, colloidal silica, and iron corrosion products. Pretreatment chemicals used in clarification such as alum, ferric chloride, or cationic polyelectrolytes can also cause fouling if not removed in the clarifier or through proper media filtration. In addition, cationic polymers may coprecipitate with negatively charged antiscalant and foul the membrane. The best available technology for determining the colloidal fouling potential of RO feed water is the measurement of silt density index (SDI). This is an important measurement to be carried out prior to designing an RO pretreatment system and on a regular basis during RO operation (2–3 times a day is recommended for surface waters) (Figure 6.4 and Tables 6.1–6.4).

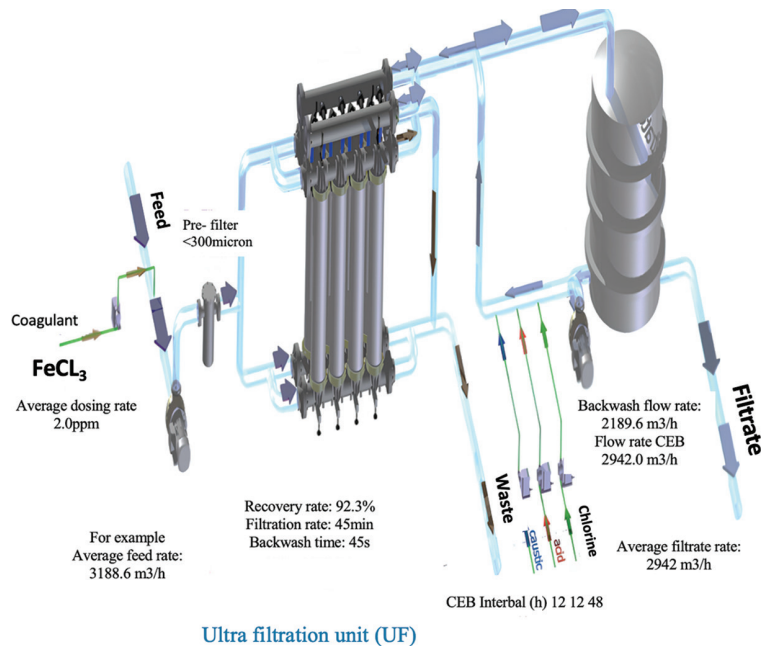


FIGURE 6.4 Ultrafiltration unit.

6.4 RO TROUBLE SHOOTING

TABLE 6.1 Trouble Shooting

<i>PERMEATE SALINITY</i>	<i>PERMEATE FLOW</i>	<i>PRESSURE DROP</i>	<i>POSSIBLE CAUSE</i>
Rapid increase	Rapid decrease	Rapid decrease	Metal oxide fouling
Marked increase	Gradual decrease	Gradual increase	Mineral scaling
Slight increase	Gradual decrease	Gradual increase	Colloidal fouling
Normal to increased	Decreased	Normal to increased	Polymerized silica
Decreased	Marked decrease	Marked increased	Biological fouling
Decreased	Decreased	Normal to increase	Organic fouling
Increased	Increased	Increased	Chlorine damage
Increased	Increased	Normal to decrease	Abrasion damages
Increased	Normal to increase	Normal to decrease	O-ring leaks at inter-connectors or adapters
Increased	Normal to increase	Normal to decrease	Glue line leaks due to permeate back pressure

TABLE 6.2 Trouble Shooting for High-Pressure Drop at First Stage

<i>PROBLEM</i>	<i>PROBABLE CAUSE</i>	<i>POSSIBLE SOLUTION</i>
Physical blockage	Something is physically blocking the front of the membranes. Pump could be damaged and passing pump shavings	Check inlet piping and front of pressure vessels for evidence of physical blockage. Check pump for damage. Remove blockage when identified
Silt or sediment	Suspended solids passing through pretreatment and settling on membranes. Media could be breaking through media filter. Pre-filters could be bypassing, leaking, or improperly installed	Open the pressure vessel to check for evidence of silt or sediment on front of membranes. Check for bypass around pre-filters. Clean if needed per silt/sediment cleaning procedure

TABLE 6.3 Trouble Shooting for High-Pressure Drop in Last Stage

<i>PROBLEM</i>	<i>PROBABLE CAUSE</i>	<i>POSSIBLE SOLUTION</i>
Scaling	Recovery rate is too high. Insufficient antiscalant dosage. Incorrect antiscalant	Reduce recovery rate. Clean system per cleaning procedure. Make sure antiscalant pump is working. Make sure dosage is correct for water analysis. Make sure antiscalant is the correct product for this application
Increased recovery rate	Operating system at too high of a recovery rate can cause an increase in pressure drop	Reduce recovery rate
Telescoping elements	Telescoped membranes can block feed channels	Replace telescoped membranes
Polymer fouling	Polymer on the front of the membranes covers the feed channels. Cationic polymer has coated polyamide membrane, due to its slight anionic nature	Open pressure vessel to check for evidence of polymer on front of membranes. Clean if needed per polymer cleaning procedure. Same as above

(Continued)

TABLE 6.3 (Continued) Trouble Shooting for High-Pressure Drop in Last Stage

<i>PROBLEM</i>	<i>PROBABLE CAUSE</i>	<i>POSSIBLE SOLUTION</i>
Iron fouling	Recovery rate too high, iron may have scaled membranes. Insufficient antiscalant dosage	Reduce recovery rate. Clean system per iron scaling cleaning procedure. Make sure antiscalant pump is working. Make sure dosage is correct for water analysis
Instrumentation	Pressure gauges are inaccurate	Calibrate pressure gauges or replace

TABLE 6.4 Trouble Shooting for Increase Conductivity

<i>PROBLEM</i>	<i>PROBABLE CAUSE</i>	<i>POSSIBLE SOLUTION</i>
Increase in feed TDS	Feed Water has changed. Rejection percentage has remained the same, but conductivity has increased	System is fine if rejection percentage has remained constant. Change feed water sources
Increase in recovery rate	Increasing recovery rate can increase volume of water recovered from membranes seeing the highest feed conductivity	Reduce recovery rate
Increase in feed pressure	Increasing feed pressure can increase volume of water recovered from membranes seeing the highest feed conductivity	Reduce feed pressure
Increase in feed temperature	Increase in feed temperature can decrease rejection rate of membranes	Decrease feed temperature
Change in feed pH	Change in feed water pH can indicate change in feed water characteristics, including conductivity. Cellulose acetate membranes operate best between pH of 4 and 7. Hydrolysis begins outside these parameters. Polyamide membranes may require acid as a scale inhibitor. Scaling can cause increase in conductivity. Acid addition can cause increased carbon dioxide formation, which is poorly rejected by membranes. Excessive pH during cleaning can cause permanent damage to membranes	Check feed conductivity. System is fine if rejection percentage has remained constant. Adjust feed pH. Check acid pump for malfunction. Check pH instrumentation. Same as above. Clean system per scaling cleaning procedure. Remove acid feed, if water analysis permits. Clean per manufacturer specifications
O-Rings	O-Rings around end adapters or inter-connectors may be leaking, broken, or missing	Profile or probe system to identify location of leak. Replace as needed
Oxidation of membranes	Excessive oxidant injection according to membrane specifications can cause loss of rejection. Cellulose acetate membranes	Remove oxidant by use of carbon filters or sodium bi-sulfite injection. See manufacturer for correct procedure and injection
Physical blockage	High solids loading. Pump failure	Clean system. Fix pump and clean system
Polymer fouling	Polymer on the front of the membranes covers the feed channels. Cationic polymer has coated polyamide membrane, due to its slight anionic nature	Open pressure vessel to check for evidence of polymer on front of membranes. Clean if needed per polymer cleaning procedure
Membrane collapse	Membrane has been over pressurized. Feed channel is plugged	Reduce pressure replace membrane if necessary. Clean system

6.5 CLEANING OF THE RO

During the normal operation, the surface of RO membrane is subjected to fouling by foreign material that may be present in the feed water such as hydrates of metal oxides, calcium precipitates, organics, and biological matter depending on feed water characteristics. The term “fouling” includes the build-up of all kinds of layers on the membrane surface, including scaling. The nature and extent of fouling depend on a number of factors, such as the quality of the feed water and the system recovery rate. The fouling of the membrane surface lowers the permeate flow rate or increases salt passage. Fouling leads to the increase in pressure drop across feed and reject sides. Typically, fouling is progressive, and if not controlled early, will impair the RO membrane element performance in a relatively short time. Cleaning is recommended when the RO shows evidence of fouling, just prior to a long-term shutdown, or as a matter of scheduled routine maintenance. Cleaning can be accomplished very effectively because of the combination of pH stability and temperature resistance of the membrane and the element components [1].

6.6 DETERMINATION OF FOULING TYPE

It is important to determine/detect the type of foulant on the membrane surface before cleaning. The best approach for this is a chemical analysis of residues collected with a membrane filter during an SDI15min value determination for pretreated water. When chemical analysis is not available, foulant can be classified by color and consistency of residue on the membrane filter. A brownish color residue will typically indicate iron fouling. White or beige color typically indicates silica, loam, calcium scale, or biological fouling. Crystalline constitution is a feature of calcium scale or inorganic colloids. Bio-fouling or organic material will – besides the smell – often show slimy/sticky consistency. [1]

6.7 SELECTION OF CLEANING PROCEDURE

Once contamination of the membrane surface has been identified, the correct cleaning procedure must be selected. If foulants are believed to be metal hydroxides, such as ferric hydroxide or calcium scale, acidic cleaning procedures are promising. If foulant is believed to be organic or biological fouling, a cleaning procedure with detergents is recommended.

6.8 ADVANTAGES OF RO WATER

There are many benefits of drinking RO water. It can eliminate bacteria, viruses, chemicals, and even heavy metals. The Environmental Protection Agency (EPA) describes RO as one of the “most effective at eliminating all disease-causing organisms and most chemical contaminants.” Taste of RO water is good and different from tap water. By removing impurities and chemicals that affect taste and odor, RO water tastes clean and refreshing. One of the notable benefits of RO filtration is the improvement in water taste and smell. Imagine the joy of enjoying a refreshing glass of water or preparing food and beverages with better-tasting ingredients. It can eliminate bottle water.

6.9 DISADVANTAGES OF RO WATER

Every coin has two sides. Like this the RO, water has some disadvantages like wasting water that could be handled through different ways. Also, for some low cost RO system, the essential minerals are removed. in terms of running cost, the RO system is expensive and require regular maintenance due to the exhaust of cartridge filters life of the membranes.

6.10 CONCLUSION

RO is the most advanced technology used in most of the family, offices, and small and big industries. Desalination due to its relatively low energy consumption, high efficiency, flexibility, ease of operation, and process economy. The RO process has been recognized by the world as a safe and beneficial method of purification. RO is also energy efficient as it does not require more electricity usage, and it just requires sufficient water pressure to power it during the entire process.

REFERENCE

1. A. A. Ahuchaogu et al. Reverse osmosis technology, its applications and nano-enabled membrane. *International Journal of Advanced Research in Chemical Science (IJARCS)*, Volume 5, Issue 2, 2018, pp. 20–26.

Wastewater Treatment

Use of Biopolymers as a Sustainable Approach

7

Ikrame Ayouch, Soumia Aboulhrouz, Ilham Joui,
Karim Dânoun, Mina Oumam, and Mohamed Zahouily

7.1 INTRODUCTION

Water contamination poses a major environmental threat, leading to the degradation of aquatic ecosystems through toxic substances [1–3]. High water quality represents, to a considerable degree, an essential element for the progress of contemporary civilization. Nevertheless, water contamination is greatly influenced by variables such as unregulated industrialization, urbanization, chemical utilization, and agricultural methods. Therefore, ensuring consistent and reliable access to uncontaminated water continues to be an ongoing challenge [4]. Several compounds that are known to be persistent pollutants contribute to water contamination. Significantly, the presence of heavy metals including cadmium, copper, zinc, arsenic, nickel, mercury, lead, silver, and chromium in the human body has been associated with the onset of chronic illnesses and, in certain instances, mortality, depending on their concentration levels [5]. In addition, discharging wastewater that contains decomposing organic substances and debris, such as pharmaceuticals, dyes, and pesticides, into lakes and seas can diminish the amount of dissolved oxygen necessary for the survival of fish and other aquatic species [6]. However, in recent years, the wastewater perception has evolved from a liability to a valuable resource capable of addressing challenges in water supply and sanitation [7–9]. Nevertheless, merely labeling wastewater as a resource is ineffective without the integration of treatment technology to facilitate this transformation [10]. Although wastewater treatment has been investigated in depth, its contribution to sustainable resource management continues to be insufficiently explored. The majority of current research focuses on different wastewater treatment methods, with little emphasis on sustainability. Approaches often mentioned include chemical, physical, and biological treatments, as well as sludge processing. These studies often provide comprehensive information on the crucial stages of wastewater treatment, including preliminary screening and pumping, primary processing, secondary processing, decontamination, and subsequent sludge handling (Figure 7.1). Additionally, a variety of nonconventional methods have been extensively studied, such as chemical precipitation [11], ion exchange [12], coagulation/flocculation [13], photolysis [14], advanced

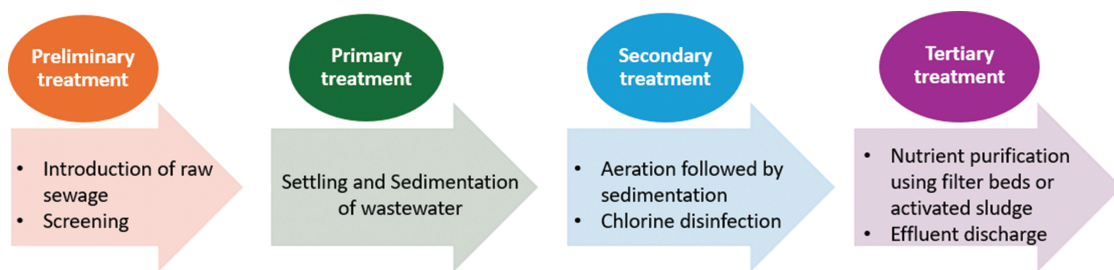


FIGURE 7.1 Phases of wastewater treatment, ranging from preliminary to tertiary stages.

oxidation [15], membrane separation [16], and adsorption. Most of these technologies are proven to offer high removal efficiencies, but each has significant drawbacks. For instance, while membrane separation is highly effective toward many pollutants, thanks to its uniform pore-size distribution, it is impaired by problems such as membrane fouling, high cost, and procedural complexity [17]. In addition, techniques such as precipitation and photolysis are more efficient in diminishing pollutants, but they face challenges due to the issue of secondary contamination [18], which raises critical concerns about sustainability. According to Libhaber et al. [19], prioritizing sustainability ensures that adequate clean water is available for the current generation while also safeguarding the access of future generations to this vital resource. To achieve this goal, it is necessary to develop and use sustainable treatment methods in order to eradicate diverse forms of contaminants and guarantee a sustainable water supply. Multiple research studies found that adsorption is the most sustainable method compared to the others, due to its effectiveness, flexibility, simplicity of application, low cost, as well as the ubiquity of a broad spectrum of adsorbent materials, both natural and synthetic.

Materials such as activated carbon, zeolites, and clays were largely used for the removal of heavy metals, dyes, and a variety of other pollutants from water and industrial effluents [20–22]. Recently, polymeric materials, especially biopolymers, have gained more popularity for wastewater treatment due to their enhanced physical and chemical characteristics, which increase their adsorption efficiency over traditional absorbents [23]. The utilization of biopolymers, particularly polysaccharides as adsorbents in wastewater treatment, is a sustainable approach due to their renewable nature and eco-friendly properties. These biopolymers are economically efficient, have a high substance adsorption capacity, are not harmful to living organisms, can be easily modified, are readily available, are compatible with living systems, have a large surface area, and are biodegradable [24]. The adsorption capacity of these biopolymers is strongly linked to their chemical structure, which consists of a high proportion of macromolecules with several coordinating groups. The wide range of functional groups present in these biopolymers enables robust interactions with different contaminants, making them adaptable and effective in the field of wastewater treatment [25]. Cellulose, chitosan, and alginate are examples of bio-based polymers commonly used as primary materials for the treatment of polluted water due to their appealing properties [22,26–30]. Cellulose, the most abundant organic material on Earth, representing over 50% of biomass and with global production exceeding 100–1,000 billion tons per year, is used for a variety of purposes, including wastewater treatment [31,32]. Chitosan is a polysaccharide obtained from chitin. The structure of chitosan contains amino groups that can undergo protonation, enabling it to dissolve in weakly acidic aqueous solutions. The solubility of this substance, combined with its exceptional characteristics, opens up distinct possibilities for the creation of revolutionary applications [33]. In addition, chitosan has amino and hydroxyl groups that act as active sites, making it a highly effective adsorbent for the removal of heavy metals and dyes from aqueous solutions [34]. Alginate acid, also known as alginate, is a linear copolymer composed of β -D-mannuronate and α -L-guluronate residues. These residues are chemically linked together in various sequences or blocks [35]. Alginate features numerous carboxyl groups, providing active sites for the uptake of wastewater pollutants.

This chapter aims to explore the use of biopolymers as environmentally friendly and sustainable adsorbents in wastewater treatment. It examines the characteristics, capabilities, and uses of biopolymers such as cellulose, chitosan, alginate, starch, and gum focusing on their ability to adsorb heavy metals and organic contaminants from water. In addition, the chapter seeks to comprehensively assess the ability of these biopolymers to replace traditional treatment materials.

7.2 COMMON BIOPOLYMERS AND THEIR CHARACTERISTICS

Biopolymers are classified into three groups according to their chemical structure: polysaccharides, synthesized biopolymers, and microbial polymers [36,37]. Natural polysaccharides, including cellulose, chitin/chitosan, alginate, guar gum, pectin, and starch, are sustainable materials, thanks to their remarkable structural properties, wide availability, lack of toxicity, and the ability to be easily modified for water treatment applications [38]. The most widespread biopolymer is cellulose, derived from the cell walls of many plants and is produced by microbial synthesis. The second most abundant biopolymer present in nature is chitin from which chitosan is produced, generally extracted from crustaceans, fungi, algae, insects, and mollusks [39]. Alginate is largely used in wastewater treatment applications either pristine or combined with other adsorbents. Commercially available alginate is commonly derived from brown algae (Phaeophyceae), such as *Laminaria hyperborea*, *Laminaria digitata*, *Laminaria japonica*, *Ascophyllum nodosum*, and *Macrocystis pyrifera* [40]. Its extraction process involves treating algae with aqueous alkaline solutions, usually NaOH. The filtrate is subjected to filtration and sodium or calcium chloride is introduced to cause alginate precipitation. Alternatively, the alginate salt can be converted into alginic acid using dilute hydrochloric acid. Finally, subsequent purification and conversion processes yield water-soluble sodium alginate powder [41]. Another largely used biopolymer in wastewater treatment is guar gum, which is obtained from guar beans, the seeds of the guar plant (*Cyamopsis tetragonoloba*). This plant is mainly grown in India and Pakistan, India being the main producer and accounting for over 80% of the world's supply. Guar gum is derived from the endosperm of guar seeds. The production method involves removing the husks, adding water to the guar seeds, crushing the seeds, and separating the resulting mixture. Once the seeds have been harvested, they undergo a drying process during which the seed is extracted from the pods. Next, the seeds are divided, and the endosperm is obtained, purified, and pulverized into a fine substance called guar gum [42,43]. Pectin, derived from citrus peel and apple pomace, is obtained by acid extraction, precipitation, and drying to produce a versatile biopolymer used in a variety of applications including water treatment [44]. Starch, obtained from crops such as corn, potatoes, and wheat, is extracted from grains or tubers by grinding, washing, and drying. This process produces a powder that is widely used in the food, paper, textile, and water purification industries [45]. Structures and sources of these biopolymers are summarized in Figure 7.2.

7.3 MODIFIED BIOPOLYMERS IN WASTEWATER TREATMENT

Biopolymers, which are derived from organic sources, have shown great promise in the field of environmental sustainability and technological advancement as well. This is mainly due to their transformation into composites, nanocomposites, or any other useful form. Such modifications on the mechanical robustness, heat resistance, and biodegradability of the biopolymers make them applicable in many

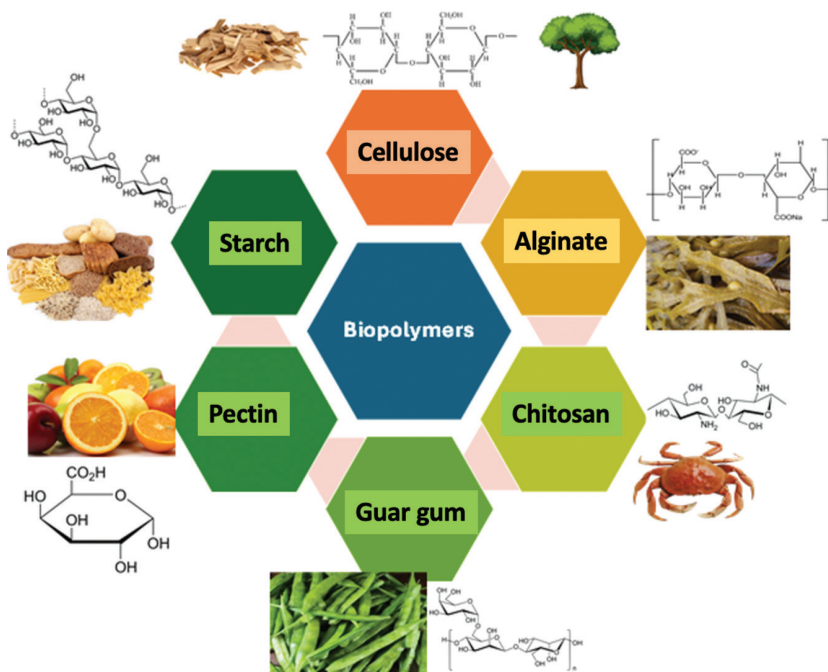


FIGURE 7.2 Chemical structure and sources of polysaccharides.

areas such as adsorbents for removal of pollutants. Several modification methods have been adopted to tailor biopolymers into valuable adsorbents. Chemical cross-linking introduces functional groups that enhance interaction with some pollutants while addition of nanoparticles (for example, graphene oxide or metal oxides) increases the surface area that can take up contaminants. Additionally, graft copolymerization can be used to introduce side chains that are selective for different compounds, hence improving water treatment efficiency. These changes make it possible not only for biopolymers to be used more widely but also assist in advancing eco-friendly and efficient environmental remediation techniques [46,47].

7.3.1 Cellulose-based Adsorbents

Cellulose is a polysaccharide composed of β -D-glucopyranose units linked by acetal bonds between the hydroxyl groups on carbons 1 and 4. Due to its ribbon-like molecular structure, cellulose demonstrates flexibility by bending or twisting rather than maintaining a flat or planar shape. Cellulose fibers have a high capacity to form hydrogen bonds, making them highly hydrophilic. These fibers have several hydroxyl groups ($-\text{OH}$) that are easily accessible and extend outward from the structure when dried. They create strong intramolecular hydrogen bonds with adjacent surrounding molecules through $\text{O}-\text{H}-\text{O}$ interactions. For example, a regenerated cellulose fiber may consist of chains of 250–500 repeating units. The characteristics of cellulose, such as hydrophilicity, chirality, and biodegradability, are a direct result of its chemical structure. The high chemical reactivity of cellulose is mainly due to the fact that it readily yields $-\text{OH}$ groups [48,49]. Due to the presence of hydroxyl functional groups in their structures, cellulosic biomaterials exhibit high adsorption capacities. This property has aroused growing interest and prompted a number of research efforts aimed at these types of materials. For instance, Wang et al. used epoxidized sugarcane cellulose fibers, together with carboxymethyl cellulose (CMC), as a new bioadsorbent for removing $\text{Pb}(\text{II})$, $\text{Zn}(\text{II})$, and $\text{Cu}(\text{II})$ ions in both single and combination pollutant systems. The study demonstrated that the incorporation of functional groups and porous

architectures greatly increased the ability to absorb heavy metal ions. Furthermore, the adsorption processes encompassed electrostatic interactions, ion exchange, and coordination between the bioadsorbent and the metal ions.

Chemical modification of cellulose has proved to be an effective method for improving adsorption capacities beyond those of raw cellulose. Chemical treatments alter the properties of cellulose, modifying its affinity for water (hydrophilic or hydrophobic) or changing its adsorption or ion exchange capacities. This results from the attachment of different functional groups to the primary and two secondary hydroxyl groups of the β -D-glucopyranose units that make up the cellulose chain [50]. Graft polymerization, etherification, oxidation, esterification, and alkaline treatment are direct cellulose modifications [48]. In their study on graft copolymerization of cellulose acetate (CA), Abdelwahab et al. [51] used a radical polymerization technique to modify CA by grafting it with an equimolar mixture of acrylic acid and acrylamide using benzoyl peroxide as the initiator. The study used both unmodified and chemically modified CA powders for the removal of Pb(II) ions. The results indicated that the unmodified CA had an adsorption capacity of only 9.4 mg/g for Pb ions. In contrast, the modified CA demonstrated a significantly enhanced capacity, reaching up to 66.67 mg/g. This behavior is due to the fact that the active binding sites for Pb(II) in CA are expected to be hydroxyl and carbonyl groups only, while modified CA has been extremely advantageous for enhancing cation exchange capacity through the addition of functional groups. Modified CA features cross-linked three-dimensional polymer networks with numerous functional groups, including OH, $-\text{CONH}_2$, $-\text{COOH}$, and $-\text{COOR}$, which can be considered as adsorption sites for ion exchange and chelation [52]. The study conducted by Shukla and Pai examines the process of adsorption of Cu(II), Ni(II), and Zn(II) ions using jute fibers that have been changed. The study also assesses the impact of the different procedures used to modify cellulose on adsorption capacity. The jute fibers underwent chemical modification by two distinct methods: dye loading, where the jute fibers were impregnated with a reactive dye (C.I. Reactive Orange 13), which forms a strong chemical bond with the cellulose structure; oxidation, where jute fibers underwent treatment with hydrogen peroxide to convert cellulose hydroxyl groups into carboxyl groups, altering the cellulose into a feeble cationic ion exchanger. Each modification approach greatly enhanced the adsorption capacity of jute fibers as compared to untreated fibers. As an illustration, jute fibers that were loaded with dye demonstrated a greater absorption of metal ions, such as 8.4 mg/g for Cu(II), in comparison to fibers that were not changed, which absorbed 4.23 mg/g for Cu(II).

Cellulose can be modified with diketene or tert-butyl acetoacetate to generate cellulose acetoacetates (CAA), which was used by Qiu et al. in an aerogel form used for static and dynamic methyl orange (MO) removal. In their work, CAA and β -cyclodextrin acetoacetate (β -CDAA) were produced by transesterification, then cross-linked with polyethyleneimine (PEI) via dynamic enamine bond formation and freeze-drying of three-dimensional network frameworks. The synthesized materials showed a maximum adsorption capacity of over 1,000 mg/g vis-à-vis MO. In addition, the materials selectively removed anionic dyes, given their abundant positive charge surface (Figure 7.3). Furthermore, aerogels comprising β -CDAA demonstrated better equilibrium adsorption efficiency under the same conditions as aerogels



FIGURE 7.3 Cross-linking strategy on functional cellulose-based aerogel for effective and selective removal of MO [53].

without β -CDAA, which was essentially associated with the particular cavity structure of β -CD and the stable inclusion compound formed by MO, thereby enhancing the aerogel's adsorption performance. The β -CDAA was shown to be not only an important constituent in building the aerogel structure but also a functional unit enhancing adsorption dynamics [53].

In addition to cellulose acetoacetate, sodium CMC is one of the most studied cellulose derivatives. CMC is an ionic polysaccharide obtained by combining cellulose with sodium hydroxide and the alkaline-catalyzed reaction of cellulose with chloroacetic acid. CMC, which includes a wide range of carboxyl and hydroxyl groups, can serve as a substrate for other polymers and procure active sites for dyes and metal ion adsorption [54]. Li et al. reported the synthesis of nanostructured adsorbents derived from carboxymethylcellulose and chitosan, which essentially involves auto-polymerization of chitosan and dopamine, doping into sodium carboxymethylcellulose and cross-linking with glutaraldehyde. The synthesized adsorbent exhibited a high capacity for complexing Cd(II) and displayed strong electrostatic interactions with Cr(VI) in acidic environments, with maximum adsorption capacities of 470.0 mg/g and 347.0 mg/g toward Cd(II) and Cr(VI), respectively [54].

In addition to the aforementioned forms of cellulose-based materials, various cellulose derivatives have been extensively researched and used as adsorbents for a wide range of water pollutants, including heavy metals, dyes, pharmaceuticals, and other contaminants. For instance, the hydrophilicity and chemical stability of adsorbents can be enhanced by incorporating hydroxyethyl cellulose (HEC), rendering them well suited for the removal of pollutants from water [55]. The derivative methylcellulose (MC) is utilized for its capacity to generate hydrogels and improve the adsorbent structure, which effectively remove contaminants such as dyes and metal ions [56]. Phosphorylated cellulose is a derivative that has phosphate groups introduced into its structure. These groups have the ability to effectively chelate metal ions, which improves their effectiveness in eliminating heavy metals [57].

7.3.2 Chitosan-based Adsorbents

In its solid state, chitosan is the only cationic polymer obtained by partial deacetylation of chitin under alkaline conditions, typically using potent sodium hydroxide or by enzymatic hydrolysis. In addition, the resulting chitosan is biocompatible, antibacterial, antiviral, nontoxic, nonallergenic, and has film-forming capabilities with high elasticity. The organic and biodegradable qualities of chitosan make it extremely appealing. Thanks to its amino ($-\text{NH}_2$) and hydroxyl ($-\text{OH}$) groups, which serve as coordination and reaction sites, chitosan is considered an exceptional adsorbent for water contaminants. Its molecular chains tend to encapsulate solid particles, minerals, heavy metals, dyes, amino acids, and proteins, effectively capturing and coagulating them. Another application for chitosan is the adsorption of radioactive materials and the removal of oil, greasy substances, toxic compounds, and aromatic chemicals. Furthermore, the incorporation of chitosan improves system efficiency, significantly reducing odors and taste [58].

Chitosan was combined with many other materials in various literature works. For instance, Chen et al. synthesized a diatomite-chitosan composite and used it for the removal of mercury ions [Hg(II)] from water. The study determined that due to the hydroxyl ($-\text{OH}$) and amino ($-\text{NH}_2$) groups in chitosan and the micropores on the diatomite surface, the composite had a remarkable affinity for Hg(II) , with a maximum adsorption capacity of 197 mg/g at a pH 3 [59]. In addition, chitosan/ TiO_2 composite nanofibrous adsorbents was developed by Razzaz et al. using two different techniques, including coating method and electrospinning method, and used for lead and copper removal from water. The findings indicate that chitosan/ TiO_2 composite nanofibers with a concentration of 2 wt.% and TiO_2 -coated chitosan nanofibers containing 2,000 mg/L of TiO_2 nanoparticles exhibit the highest adsorption capacities for heavy metals. The adsorptive capacity of different metal ions onto the nanofibrous adsorbent decreased in the following sequence: Cu(II) (715 mg/g), Pb(II) (570 mg/g), Co(II) (510 mg/g), and Ni(II) (45 mg/g). This optimum performance was recorded at a pH of 6, an equilibrium time of 30 minutes,

TABLE 7.1 Utilization of Chitosan-Based Materials for Heavy Metal and Dye Removal

<i>CHITOSAN-BASED ADSORBENT</i>	<i>POLLUTANT</i>	<i>ADSORPTION CAPACITY (MG/G)</i>	<i>REFERENCES</i>
Chitosan–polyvinyl alcohol/ glutaraldehyde	Cd(II)	143	[62]
Chitosan/polyacrylic acid	Ni(II)	435	[63]
Magnetic granule sludge/ chitosan	Pb(II)	97.97	[64]
Chitosan/hydroxyapatite	Co(II)	213.8	[65]
Chitosan–alginate nanoparticles	Hg(II)	217.39	[66]
Hydroxyapatite/chitosan/ montmorillonite	Indigo carmine	243.18	[67]
Chitosan-coated cotton fiber composite	Brilliant red F3B	169.33	[68]
Chitosan-coated cotton cloth	Methyl orange	172.17	[69]
Sulfate-cross-linked chitosan	Congo red	91.8	[70]
Zn-MOF/chitosan composite	Methyl orange	202	[71]

and a temperature of 45°C [60]. The effectiveness of chitosan/TiO₂ composite nanofibrous adsorbents in the removal of heavy metals is attributed to a synergistic impact of electrostatic attraction, ion exchange, complexation, photocatalytic activity, and the large surface area allowed by the nanofibrous structure. These techniques contribute synergistically to achieving significant adsorption capacities, making this material a very promising option for water purification applications. Chitosan was also used for the adsorption of many dyes including methylene blue (MB), Congo red (CR), MO, brilliant red (BR), crystal violet (CR), and indigo carmine (IC) [61]. Shukla et al. studied the removal of MB using a cross-linked chitosan-activated charcoal composite material and found that the synthesized material effectively removed 95% of the MB present in the wastewater, achieving a maximum adsorption capacity of 625 mg/g. Table 7.1 showcases various chitosan-based materials utilized for the removal of heavy metals and dyes.

7.3.3 Alginate-based Adsorbents

Derived from brown algae, alginate remains a highly effective biopolymer for the development of wastewater treatment due to its biocompatibility, biodegradability, and ability to create hydrogels when cross-linked with divalent cations such as calcium. The intrinsic characteristics of alginate, combined with its strong attraction to various contaminants, make it a highly attractive candidate for environmental decontamination. Recent research has highlighted the effectiveness of alginate-based adsorbents for the selective removal of heavy metals. Alginate-based adsorbents have been extensively exploited for the removal of heavy metals from surface waters. Recent studies have highlighted advances in alginate-based hydrogels and beads that effectively capture metal ions such as lead and cadmium from polluted water sources. The effectiveness of these adsorbents is explained by their ion exchange characteristics and their large surface area, which favor the formation of complexes with metal ions. The strong arsenic and Cd adsorption capacities demonstrated by alginate composites incorporating magnetic nanoparticles (MnO₂) are a case in point and demonstrate the versatility of alginate in meeting

different remediation requirements [72]. In addition, Ayouch et al. [25] produced an adsorbent based on calcium alginate beads and evaluated its ability to remove lead cadmium (Cd(II)) from water-based solutions. At an optimum pH of 5, the adsorbent demonstrated a maximum adsorption capacity of 83.06 mg/g, suggesting its potential for treating water polluted by heavy metal residues [25]. The adaptability of alginate also applies to the adsorption of organic dyes and pharmaceuticals, which pose difficulties when disposed of in wastewater due to their intrinsically stable chemical composition. Analysis of modifications to alginate, including functional groups or composites, such as the incorporation of graphene oxide, has made it possible to improve adsorption properties. Physical and chemical adsorption methods are used in these modifications to improve the efficiency of removing complex organic compounds from wastewater streams [73]. Furthermore, innovative approaches have been studied to increase the adsorption efficiency and recyclability of alginate materials by modifying them. The use of clay modified alginate beads is one approach that has shown promise in improving the adsorptive removal of heavy metals. This is due to the enhanced interaction between the modified alginate and the metal ions, facilitated by chelation and electrostatic attraction [29,30]. In addition, the incorporation of photocatalytic elements such as ZnO particles into alginate structures has created opportunities for the simultaneous adsorption and decomposition of pollutants including dyes such as MB, highlighting the dynamic capabilities of alginate in environmental processes [74].

7.4 BIOPOLYMERS IN WASTEWATER TREATMENT: BEYOND ADSORPTION

As well as adsorption, biopolymers have applications in other wastewater treatment processes, each exploiting the distinct characteristics of these natural materials.

Biopolymers are highly effective as coagulants and flocculants due to their high electron charge density, which enables them to collect particles suspended in water. This procedure is designed to improve sedimentation and particle removal in wastewater treatment. For example, the high molecular weight and reactive amino and hydroxyl functional groups of the natural polymer chitosan are responsible for its cationic properties, which contribute to its depolluting effectiveness. These characteristics enable the neutralization of charges and enhance the coagulation and flocculation of contaminants through cross-linking processes. A study into the effectiveness of chitosan in coagulation and flocculation for dye removal revealed that the protonated amine groups of chitosan exert an electrostatic attraction on the anionic dyes. This interaction results in charge neutralization and enhances the flocculation process, facilitating the fixation and decantation of dye agglomerates by a bridging mechanism [75]. However, for anionic natural polymers such as cellulose or tannin, the addition of cations is necessary to facilitate the flocculation of anionic pollutants in wastewater. To neutralize the charge of negatively charged pollutants, cationic agents such as chitosan or inorganic metal salts (e.g. aluminum or iron salts) are used. During charge neutralization, anionic polymers such as cellulose, sodium alginate, or tannin, which have negatively charged backbones, can grow within the solution. The present addition introduces loops and tails that effectively enable the process of bridging and aggregation of flocs [76].

Biopolymers are also being included in membrane technologies for filtration purposes. Nanocomposite membranes using biopolymers such as chitosan or alginate have been synthesized to improve filtration efficiency and antifouling characteristics. These membranes are highly effective at removing tiny particles and pollutants from water, making them well suited for integration into microfiltration and ultrafiltration systems [77].

7.5 CONCLUSION

The combination of environmental friendliness and functional performance makes biopolymers a key element of sustainability in wastewater treatment. An in-depth study of cellulose, chitosan, and alginate has shown their significant capacity to effectively adsorb and remove heavy metals and organic pollutants from water. The incorporation of these biopolymers corresponds not only to ecological conservation objectives but also to economic feasibility, which means a significant transition toward sustainable water management mechanisms. As research and technological advances continue, biopolymers are set to play an increasingly crucial role, offering a future where clean water is readily available and sustainability is not just a goal, but a tangible achievement.

REFERENCES

1. D. Cheng, H.H. Ngo, W. Guo, S.W. Chang, D.D. Nguyen, Y. Liu, Q. Wei, D. Wei, A critical review on antibiotics and hormones in swine wastewater: Water pollution problems and control approaches. *J. Hazard. Mater.* 387 (2020) 121682. <https://doi.org/https://doi.org/10.1016/j.jhazmat.2019.121682>.
2. B.C. Hodges, E.L. Cates, J.-H. Kim, Challenges and prospects of advanced oxidation water treatment processes using catalytic nanomaterials. *Nat. Nanotechnol.* 13 (2018) 642–650. <https://doi.org/10.1038/s41565-018-0216-x>.
3. F. Khodabandloo, S. Shahsavarifar, B. Nayebe, K.P. Niavol, B. Nayebe, R.S. Varma, J.H. Cha, H.W. Jang, D. Kim, M. Shokouhimehr, Applications of nanostructured semiconductor photocatalysts for the decontamination of assorted pollutants from wastewater. *Inorg. Chem. Commun.* 157 (2023) 111357. <https://doi.org/https://doi.org/10.1016/j.inoche.2023.111357>.
4. M. Vakili, M. Rafatullah, B. Salamatina, A.Z. Abdullah, M.H. Ibrahim, K.B. Tan, Z. Gholami, P. Amouzgar, Application of chitosan and its derivatives as adsorbents for dye removal from water and wastewater: A review. *Carbohydr. Polym.* 113 (2014) 115–130. <https://doi.org/https://doi.org/10.1016/j.carbpol.2014.07.007>.
5. T. Russo, P. Fucile, R. Giacometti, F. Sannino, Sustainable removal of contaminants by biopolymers : and future perspectives. *Processes.* 9 (2021) 719.
6. K. Chojnacka, A. Witek-Krowiak, K. Moustakas, D. Skrzypczak, K. Mikula, M. Loizidou, A transition from conventional irrigation to fertigation with reclaimed wastewater: Prospects and challenges. *Renew. Sustain. Energy Rev.* 130 (2020) 109959. <https://doi.org/https://doi.org/10.1016/j.rser.2020.109959>.
7. S. Nair K, B. Manu, A. Azhoni, Sustainable treatment of paint industry wastewater: Current techniques and challenges. *J. Environ. Manage.* 296 (2021) 113105. <https://doi.org/https://doi.org/10.1016/j.jenvman.2021.113105>.
8. V. Navarro-Ramírez, J. Ramírez-Hernandez, M. Gil-Samaniego, J. Eliana Rodríguez-Burgueño, Methodological frameworks to assess sustainable water resources management in industry: A review. *Ecol. Indic.* 119 (2020) 106819. <https://doi.org/https://doi.org/10.1016/j.ecolind.2020.106819>.
9. Z. Liao, Z. Chen, A. Xu, Q. Gao, K. Song, J. Liu, H.-Y. Hu, Wastewater treatment and reuse situations and influential factors in major Asian countries. *J. Environ. Manage.* 282 (2021) 111976. <https://doi.org/https://doi.org/10.1016/j.jenvman.2021.111976>.
10. S. Ofori, A. Puškáčová, I. Růžicková, J. Wanner, Treated wastewater reuse for irrigation: Pros and cons. *Sci. Total Environ.* 760 (2021) 144026. <https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.144026>.
11. R. Wu, Removal of heavy metal ions from industrial wastewater based on chemical precipitation method. *Ekoloji* 28 (2019) 2443–2452.
12. A. Bashir, L.A. Malik, S. Ahad, T. Manzoor, M.A. Bhat, G.N. Dar, A.H. Pandith, Removal of heavy metal ions from aqueous system by ion-exchange and biosorption methods. *Environ. Chem. Lett.* 17 (2019) 729–754. <https://doi.org/10.1007/s10311-018-00828-y>.

13. M.H. Mohamed Noor, M.F.Z. Mohd Azli, N. Ngadi, I. Mohammed Inuwa, L. Anako Opotu, M. Mohamed, Optimization of sonication-assisted synthesis of magnetic *Moringa oleifera* as an efficient coagulant for palm oil wastewater treatment. *Environ. Technol. Innov.* 25 (2022) 102191. <https://doi.org/https://doi.org/10.1016/j.eti.2021.102191>.
14. S. Sha, Z. Dong, Y. Gao, H. Hashim, C.T. Lee, C. Li, In-situ removal of residual antibiotics (enrofloxacin) in recirculating aquaculture system: Effect of ultraviolet photolysis plus biodegradation using immobilized microbial granules. *J. Clean. Prod.* 333 (2022) 130190. <https://doi.org/10.1016/j.jclepro.2021.130190>.
15. Z. Wu, Y. Wang, Z. Xiong, Z. Ao, S. Pu, G. Yao, B. Lai, Core-shell magnetic $\text{Fe}_3\text{O}_4@\text{Zn/Co-ZIFs}$ to activate peroxymonosulfate for highly efficient degradation of carbamazepine. *Appl. Catal. B Environ.* 277 (2020) 119136. <https://doi.org/10.1016/j.apcatb.2020.119136>.
16. M. Zeng, I. Echols, P. Wang, S. Lei, J. Luo, B. Peng, L. He, L. Zhang, D. Huang, C. Mejia, L. Wang, M.S. Mannan, Z. Cheng, Highly biocompatible, underwater superhydrophilic and multifunctional biopolymer membrane for efficient oil–water separation and aqueous pollutant removal. *ACS Sustain. Chem. Eng.* 6 (2018) 3879–3887. <https://doi.org/10.1021/acssuschemeng.7b04219>.
17. C. Algieri, V. Pugliese, G. Coppola, S. Curcio, V. Calabro, S. Chakraborty, Arsenic removal from groundwater by membrane technology: Advantages, disadvantages, and effect on human health. *Groundw. Sustain. Dev.* 19 (2022). <https://doi.org/10.1016/j.gsd.2022.100815>.
18. M.B. Bahrodin, N.S. Zaidi, N. Hussein, M. Sillanpää, D.D. Prasetyo, A. Syafiuddin, Recent advances on coagulation-based treatment of wastewater: transition from chemical to natural coagulant. *Curr. Pollut. Reports.* 7 (2021) 379–391. <https://doi.org/10.1007/s40726-021-00191-7>.
19. M. Libhaber, Á. Orozco-Jaramillo, Sustainable treatment and reuse of municipal wastewater: For decision makers and practicing engineers, (2015). <https://doi.org/10.2166/9781780400631>.
20. T.D. Nguyen, T.M.P. Nguyen, H.T. Van, V.Q. Nguyen, L.H. Nguyen, T.D. Nguyen, T.H. V Nguyen, T.H.H. Chu, T.H. Nguyen, L.T. Ha, N.D. Vinh, V.N. Thai, K.A. Nguyen, P.Q. Thang, Adsorption removal of ammonium from aqueous solution using Mg/Al layered double hydroxides-zeolite composite. *Environ. Technol. Innov.* 25 (2022). <https://doi.org/10.1016/j.eti.2021.102244>.
21. P. Vijetha, M. Ramesh Naidu, N. Satyasree, P. Rajasekhar Reddy, Adsorption of methylene blue from aqueous solutions using *Tamarindus indica*. *Res. J. Pharm. Technol.* 10 (2017) 2557–2560. <https://doi.org/10.5958/0974-360X.2017.00452.8>.
22. C. Hu, P. Zhu, M. Cai, H. Hu, Q. Fu, Comparative adsorption of Pb(II), Cu(II) and Cd(II) on chitosan saturated montmorillonite: Kinetic, thermodynamic and equilibrium studies. *Appl. Clay Sci.* 143 (2017) 320–326. <https://doi.org/10.1016/j.clay.2017.04.005>.
23. M. Tanzifi, M. Tavakkoli Yarak, M. Karami, S. Karimi, A. Dehghani Kiadehi, K. Karimipour, S. Wang, Modelling of dye adsorption from aqueous solution on polyaniline/carboxymethyl cellulose/ TiO_2 nanocomposites. *J. Colloid Interface Sci.* 519 (2018) 154–173. <https://doi.org/10.1016/j.jcis.2018.02.059>.
24. A.M. Ahmed, M.L. Mekonnen, K.N. Mekonnen, Review on nanocomposite materials from cellulose, chitosan, alginate, and lignin for removal and recovery of nutrients from wastewater. *Carbohydr. Polym. Technol. Appl.* 6 (2023) 100386. <https://doi.org/10.1016/j.carpta.2023.100386>.
25. I. Ayouch, I. Barrak, Z. Kassab, M. El Achaby, A. Barhoun, K. Draoui, Impact of the drying process on the efficiency of alginate beads for cadmium removal from water: Kinetic, isotherm and thermodynamic study. *Environ. Technol. Innov.* 20 (2020) 539–547. <https://doi.org/10.1016/j.eti.2020.101157>.
26. M. El Achaby, M. Ruesgas-Ramón, N.E.H. Fayoud, M.C. Figueroa-Espinoza, V. Trabadelo, K. Draoui, H. Ben Youcef, Bio-sourced porous cellulose microfibrils from coffee pulp for wastewater treatment. *Cellulose.* 26 (2019) 3873–3889. <https://doi.org/10.1007/s10570-019-02344-w>.
27. C. Sairam Sundaram, N. Viswanathan, S. Meenakshi, Uptake of fluoride by nano-hydroxyapatite/chitosan, a bioinorganic composite. *Bioresour. Technol.* 99 (2008) 8226–8230. <https://doi.org/10.1016/j.biortech.2008.03.012>.
28. R. El, K. Billah, I. Ayouch, Y. Abdellaoui, Z. Kassab, Chitosan/nanohydroxyapatite biocomposite for divalent cadmium ions removal from water (n.d.), pp. 1–34. *Polymers* **2023**, 15(6), 1524; <https://doi.org/10.3390/polym15061524>.
29. I. Barrak, I. Ayouch, Z. Kassab, M. El Achaby, A. Barhoun, K. Draoui, Sodium alginate encapsulated Moroccan clay as eco-friendly and efficient adsorbent for copper ions from aqueous medium, Mater. Today Proc. (2021). <https://doi.org/https://doi.org/10.1016/j.matpr.2021.07.392>.
30. I. Ayouch, I. Barrak, Z. Kassab, M. El Achaby, A. Barhoun, K. Draoui, Improved recovery of cadmium from aqueous medium by alginate composite beads filled by bentonite and phosphate washing sludge. *Colloids Surfaces A Physicochem. Eng. Asp.* (2020) 125305. <https://doi.org/10.1016/j.colsurfa.2020.125305>.
31. X. Li, C. Wan, T. Tao, H. Chai, Q. Huang, Y. Chai, Y. Wu, An overview of the development status and applications of cellulose-based functional materials. Springer, Netherlands (2024). <https://doi.org/10.1007/s10570-023-05616-8>.

32. G.H. Delmas, J.H. Banoub, M. Delmas, Lignocellulosic biomass refining: a review promoting a method to produce sustainable hydrogen, fuels, and products. *Waste Biomass Valoriz.* 13 (2022) 2477–2491. <https://doi.org/10.1007/s12649-021-01624-6>.
33. H.M. Ibrahim, E.M.R.E. Zairy, Chitosan as a biomaterial: structure, properties, and electrospun nanofibers (n.d.). in book: Concepts, Compounds and the Alternatives of Antibacterials, Edited by Varaprasad Bobbarala. IntechOpen, DOI: 10.5772/61300
34. Q. Luo, X. Huang, Y. Luo, H. Yuan, T. Ren, X. Li, D. Xu, X. Guo, Y. Wu, Fluorescent chitosan-based hydrogel incorporating titanate and cellulose nanofibers modified with carbon dots for adsorption and detection of Cr(VI). *Chem. Eng. J.* 407 (2021) 127050. <https://doi.org/10.1016/j.cej.2020.127050>.
35. S.R. Choe, Y. Haldorai, S.C. Jang, M. Rethinasabapathy, Y.C. Lee, Y.K. Han, Y.S. Jun, C. Roh, Y.S. Huh, Fabrication of alginate/humic acid/Fe-aminoclay hydrogel composed of a grafted-network for the efficient removal of strontium ions from aqueous solution. *Environ. Technol. Innov.* 9 (2018) 285–293. <https://doi.org/10.1016/j.eti.2017.12.008>.
36. G.P. Udayakumar, S. Muthusamy, B. Selvaganesh, N. Sivarajasekar, K. Rambabu, S. Sivamani, N. Sivakumar, J.P. Maran, A. Hosseini-Bandegharai, Ecofriendly biopolymers and composites: Preparation and their applications in water-treatment. *Biotechnol. Adv.* 52 (2021) 107815. <https://doi.org/10.1016/j.biotechadv.2021.107815>.
37. S. Bin Park, E. Lih, K.S. Park, Y.K. Joung, D.K. Han, Biopolymer-based functional composites for medical applications. *Prog. Polym. Sci.* 68 (2017) 77–105. <https://doi.org/10.1016/j.progpolymsci.2016.12.003>.
38. M. Nasrollahzadeh, M. Sajjadi, S. Iravani, R.S. Varma, Starch, cellulose, pectin, gum, alginate, chitin and chitosan derived (nano)materials for sustainable water treatment: A review. *Carbohydr. Polym.* 251 (2021) 116986. <https://doi.org/10.1016/j.carbpol.2020.116986>.
39. S. Hema, G. U Chandran, P. R. Jyothi, S. Sambhudevan, Biomedical applications of chitin. In: S. Thomas, A.R. Ajitha, C. Jose Chirayil, B. Thomas (Eds.), *Handbook of Biopolymers*. Springer Nature Singapore, Singapore (2022), pp. 1–28. https://doi.org/10.1007/978-981-16-6603-2_25-1.
40. O. Smidsrød, G. Skjåk-Braek, Alginate as immobilization matrix for cells. *Trends Biotechnol.* 8 (1990) 71–78. [https://doi.org/10.1016/0167-7799\(90\)90139-o](https://doi.org/10.1016/0167-7799(90)90139-o).
41. K.Y. Lee, D.J. Mooney, Alginate: properties and biomedical applications. *Prog. Polym. Sci.* 37 (2012) 106–126. <https://doi.org/10.1016/j.progpolymsci.2011.06.003>.
42. D. Mudgil, Partially hydrolyzed guar gum: preparation and properties. In: T. J. Gutiérrez (Ed.), *Polymers for Food Applications*. Springer, Cham, (2018), pp. 529–549. https://doi.org/10.1007/978-3-319-94625-2_20.
43. W. Rutenberg Morton, R. Molnar Thomas R, Preparation of Guar Gum, US-4269975-A, Nat Starch Chem Corp, Cincinnati, OH (1981).
44. R. Surolia, A. Singh, Pectin: Structure, Specification, production, applications and various emerging sources: A review. In: M. Thakur (Ed.), *Sustainable Food Systems (Volume II): SFS: Novel Sustainable Green Technologies, Circular Strategies, Food Safety & Diversity*. Springer Nature Switzerland, Cham (2024), pp. 267–282. https://doi.org/10.1007/978-3-031-46046-3_13.
45. L. Wang, L. Tong, Production and properties of starch: current research. *Molecules* 29 (2024) 4–7. <https://doi.org/10.3390/molecules29030646>.
46. M. Annu, S. Mittal, Tripathi, D.K. Shin, Biopolymeric nanocomposites for wastewater remediation: an overview on recent progress and challenges. *Polymers (Basel)* 16 (2024). <https://doi.org/10.3390/polym16020294>.
47. A. Khan, S. Malik, N. Ali, M. Bilal, Y. Yang, M.S. Akhter, V. Kumar, H.M.N. Iqbal, polymer nanocomposites for wastewater treatment (2022). <https://doi.org/10.1201/9781003239956-18>.
48. D. Klemm, B. Heublein, H.-P. Fink, A. Bohn, Cellulose: fascinating biopolymer and sustainable raw material. *Angew. Chemie Int. Ed.* 44 (2005) 3358–3393. <https://doi.org/https://doi.org/10.1002/anie.200460587>.
49. K. Oksman, Y. Aitomäki, A.P. Mathew, G. Siqueira, Q. Zhou, S. Butylina, S. Tanpichai, X. Zhou, S. Hooshmand, Review of the recent developments in cellulose nanocomposite processing. *Compos. A Appl. Sci. Manuf.* 83 (2016) 2–18. <https://doi.org/10.1016/j.compositesa.2015.10.041>.
50. N.A. Fakhre, B.M. Ibrahim, The use of new chemically modified cellulose for heavy metal ion adsorption. *J. Hazard. Mater.* 343 (2018) 324–331. <https://doi.org/10.1016/j.jhazmat.2017.08.043>.
51. N.A. Abdelwahab, N.S. Ammar, H.S. Ibrahim, Graft copolymerization of cellulose acetate for removal and recovery of lead ions from wastewater. *Int. J. Biol. Macromol.* 79 (2015) 913–922. <https://doi.org/10.1016/j.jbiomac.2015.05.022>.
52. X. Wang, Y. Zheng, A. Wang, Fast removal of copper ions from aqueous solution by chitosan-g-poly(acrylic acid)/attapulgitite composites. *J. Hazard. Mater.* 168 (2009) 970–977. <https://doi.org/10.1016/j.jhazmat.2009.02.120>.
53. C. Qiu, Y. Li, H. Liu, X. Wang, S. Hu, H. Qi, A novel crosslinking strategy on functional cellulose-based aerogel for effective and selective removal of dye. *Chem. Eng. J.* 463 (2023) 142404. <https://doi.org/10.1016/j.cej.2023.142404>.

54. S.S. Li, X.L. Wang, Q. Da An, Z.Y. Xiao, S.R. Zhai, L. Cui, Z.C. Li, Upon designing carboxyl methylcellulose and chitosan-derived nanostructured sorbents for efficient removal of Cd(II) and Cr(VI) from water. *Int. J. Biol. Macromol.* 143 (2020) 640–650. <https://doi.org/10.1016/j.ijbiomac.2019.12.053>.
55. I. Ayouch, I. Kassem, Z. Kassab, I. Barrak, A. Barhoun, J. Jacquemin, K. Draoui, M. El Achaby, Crosslinked carboxymethyl cellulose-hydroxyethyl cellulose hydrogel films for adsorption of cadmium and methylene blue from aqueous solutions. *Surf. Interfaces* 24 (2021) 101124. <https://doi.org/10.1016/j.surfin.2021.101124>.
56. A. Nasiri, S. Rajabi, M. Hashemi, CoFe₂O₄@Methylcellulose/AC as a New, Green, and Eco-friendly Nano-magnetic adsorbent for removal of Reactive Red 198 from aqueous solution. *Arab. J. Chem.* 15 (2022) 103745. <https://doi.org/10.1016/j.arabjc.2022.103745>.
57. X. Luo, J. Yuan, Y. Liu, C. Liu, X. Zhu, X. Dai, Z. Ma, F. Wang, Improved solid-phase synthesis of phosphorylated cellulose microsphere adsorbents for highly effective Pb²⁺ removal from water: batch and fixed-bed column performance and adsorption mechanism (2017). <https://doi.org/10.1021/acssuschemeng.7b00472>.
58. A. Basem, D.J. Jasim, H.S. Majdi, R.M. Mohammed, M. Ahmed, A.H. Al-Rubaye, E. Kianfar, Adsorption of heavy metals from wastewater by chitosan: A review. *Results Eng.* 23 (2024) 102404. <https://doi.org/10.1016/j.rineng.2024.102404>.
59. Y. Fu, X. Xu, Y. Huang, J. Hu, Q. Chen, Y. Wu, Preparation of new diatomite–chitosan composite materials and their adsorption properties and mechanism of Hg(II). *R. Soc. Open Sci.* 4 (2017). <https://doi.org/10.1098/rsos.170829>.
60. A. Razzaz, S. Ghorban, L. Hosayni, M. Irani, M. Aliabadi, Chitosan nanofibers functionalized by TiO₂ nanoparticles for the removal of heavy metal ions. *J. Taiwan Inst. Chem. Eng.* 58 (2016) 333–343.
61. L. Hevira, J.O. Ighalo, D. Sondari, Chitosan-based polysaccharides for effective synthetic dye adsorption. *J. Mol. Liq.* 393 (2024) 123604. <https://doi.org/10.1016/j.molliq.2023.123604>.
62. M. Kumar, B.P. Tripathi, V.K. Shahi, Crosslinked chitosan/polyvinyl alcohol blend beads for removal and recovery of Cd(II) from wastewater. *J. Hazard. Mater.* 172 (2009) 1041–1048. <https://doi.org/https://doi.org/10.1016/j.jhazmat.2009.07.108>.
63. D. Hritcu, G. Dodi, M.I. Popa, Heavy metal ions adsorption on chitosan-magnetite microspheres. *Int. Rev. Chem. Eng.* 4 (2012) 364–368.
64. T. Liu, X. Han, Y. Wang, L. Yan, B. Du, Q. Wei, D. Wei, Magnetic chitosan/anaerobic granular sludge composite: Synthesis, characterization and application in heavy metal ions removal. *J. Colloid Interface Sci.* 508 (2017) 405–414. <https://doi.org/https://doi.org/10.1016/j.jcis.2017.08.067>.
65. M. Aliabadi, M. Irani, J. Ismaeli, S. Najafzadeh, Design and evaluation of chitosan/hydroxyapatite composite nanofiber membrane for the removal of heavy metal ions from aqueous solution. *J. Taiwan Inst. Chem. Eng.* 45 (2014) 518–526. <https://doi.org/https://doi.org/10.1016/j.jtice.2013.04.016>.
66. R. Dubey, J. Bajpai, A.K. Bajpai, Chitosan-alginate nanoparticles (CANPs) as potential nanosorbent for removal of Hg (II) ions. *Environ. Nanotechnol. Monit. Manag.* 6 (2016) 32–44. <https://doi.org/https://doi.org/10.1016/j.enmm.2016.06.008>.
67. M. Joudi, H. Nasserlah, H. Hafdi, J. Mouldar, B. Hatimi, M.A. El Mhammedi, M. Bakasse, Synthesis of an efficient hydroxyapatite–chitosan–montmorillonite thin film for the adsorption of anionic and cationic dyes: adsorption isotherm, kinetic and thermodynamic study. *SN Appl. Sci.* 2 (2020) 1078. <https://doi.org/10.1007/s42452-020-2848-3>.
68. M.S. Salman, M.C. Sheikh, M.M. Hasan, M.N. Hasan, K.T. Kubra, A.I. Rehan, M.E. Awual, A.I. Rasee, R.M. Waliullah, M.S. Hossain, M.A. Khaleque, A.K.D. Alsukaibi, H.M. Alshammari, M.R. Awual, Chitosan-coated cotton fiber composite for efficient toxic dye encapsulation from aqueous media. *Appl. Surf. Sci.* 622 (2023) 157008. <https://doi.org/https://doi.org/10.1016/j.apsusc.2023.157008>.
69. R.M. Waliullah, A.I. Rehan, M.E. Awual, A.I. Rasee, M.C. Sheikh, M.S. Salman, M.S. Hossain, M.M. Hasan, K.T. Kubra, M.N. Hasan, H.M. Marwani, A. Islam, M.M. Rahman, M.A. Khaleque, M.R. Awual, Optimization of toxic dye removal from contaminated water using chitosan-grafted novel nanocomposite adsorbent. *J. Mol. Liq.* 388 (2023) 122763. <https://doi.org/https://doi.org/10.1016/j.molliq.2023.122763>.
70. C. Jeyaseelan, N. Chaudhary, R. Jugade, Sulphate-crosslinked chitosan as an adsorbent for the removal of Congo red dye from aqueous solution. *Air, Soil Water Res.* 11 (2018) 1178622118811680. <https://doi.org/10.1177/1178622118811680>.
71. C. Niu, N. Zhang, C. Hu, C. Zhang, H. Zhang, Y. Xing, Preparation of a novel citric acid-crosslinked Zn-MOF/chitosan composite and application in adsorption of chromium(VI) and methyl orange from aqueous solution. *Carbohydr. Polym.* 258 (2021) 117644. <https://doi.org/https://doi.org/10.1016/j.carbpol.2021.117644>.
72. J. Shim, M. Kumar, S. Mukherjee, R. Goswami, Sustainable removal of pernicious arsenic and cadmium by a novel composite of MnO₂ impregnated alginate beads: A cost-effective approach for wastewater treatment. *J. Environ. Manage.* 234 (2019) 8–20. <https://doi.org/https://doi.org/10.1016/j.jenvman.2018.12.084>.

73. K.Z. Elwakeel, M.M. Ahmed, A. Akhdhar, M.G.M. Sulaiman, Z.A. Khan, Recent advances in alginate-based adsorbents for heavy metal retention from water: a review. *Desalin. Water Treat.* 272 (2022) 50–74. <https://doi.org/10.5004/dwt.2022.28834>.
74. A. Zyoud, A.H. Zyoud, S.H. Zyoud, H. Nassar, S.H. Zyoud, N. Qamhieh, A. Hajamohideen, H.S. Hilal, Photocatalytic degradation of aqueous methylene blue using ca-alginate supported ZnO nanoparticles: point of zero charge role in adsorption and photodegradation. *Environ. Sci. Pollut. Res.* 30 (2023) 68435–68449. <https://doi.org/10.1007/s11356-023-27318-1>.
75. C.S. Lee, J. Robinson, M.F. Chong, A review on application of flocculants in wastewater treatment. *Process Saf. Environ. Prot.* 92 (2014) 489–508. <https://doi.org/https://doi.org/10.1016/j.psep.2014.04.010>.
76. C. Zhao, J. Zhou, Y. Yan, L. Yang, G. Xing, H. Li, P. Wu, M. Wang, H. Zheng, Application of coagulation/flocculation in oily wastewater treatment: A review. *Sci. Total Environ.* 765 (2021) 142795. <https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.142795>.
77. S. Divya, T.H. Oh, Polymer nanocomposite membrane for wastewater treatment: a critical review. *Polymers (Basel)*. 14 (2022) 1732.

Application of *Moringa oleifera* Plant for Water Treatment

8

Karim Dânoun, Soumia Aboulhrouz,
and Mohamed Zahouily

8.1 INTRODUCTION

Access to clean water is a fundamental human right and a pressing global challenge, with an estimated 2.2 billion people worldwide lacking safely managed drinking water services [1]. This crisis is particularly acute in developing regions, where conventional water treatment infrastructure is often limited or absent. Conventional water and wastewater treatment methods often rely on energy-intensive processes and the use of synthetic chemicals, which can be financially and environmentally unsustainable, especially for resource-constrained communities. In this context, the search for alternative, cost-effective, and environmentally friendly treatment solutions has gained significant momentum. Coagulation represents a fundamental technology employed in water treatment processes, wherein a variety of coagulants are utilized to facilitate the removal of contaminants and produce potable water for diverse applications [2,3]. The conventional methods employed for the treatment of water, whether to produce tap water, the treatment of wastewater or the recycling of water, often rely on the use of chemical coagulants mainly aluminium sulphate ($\text{Al}_2(\text{SO}_4)_3$) and ferric sulphate ($\text{Fe}_2(\text{SO}_4)_3$). However, the utilization of these synthetic coagulants can be associated with environmental and economic concerns, particularly in developing regions with limited access to advanced water treatment technologies. In this regard, the application of *Moringa oleifera* (MO) has emerged as a promising and sustainable alternative for water treatment. This recognition is reflected in the scientific community's increasing focus on the subject, as evidenced by a notable upward trend in research activities (Figure 8.1). A bibliometric analysis of the Web of Science database revealed that 971 relevant articles were published between 2000 and 2024, demonstrating a growing interest in the subject and highlighting the ongoing exploration of MO's applications in sustainable water solutions. More specifically, MO seeds contain water-soluble, positively charged proteins that exhibit remarkable coagulation properties, rendering them an effective natural coagulant, designated as *Moringa oleifera* coagulant (MOC). Based on this understanding, previous studies have demonstrated the efficacy of water-extracted MOC in achieving over 60% removal of turbidity for highly turbid surface waters, with turbidity levels up to 750 NTU. These findings provide empirical evidence supporting the coagulation capabilities of the MO extract, showcasing its ability to effectively treat water sources with extremely high turbidity levels.

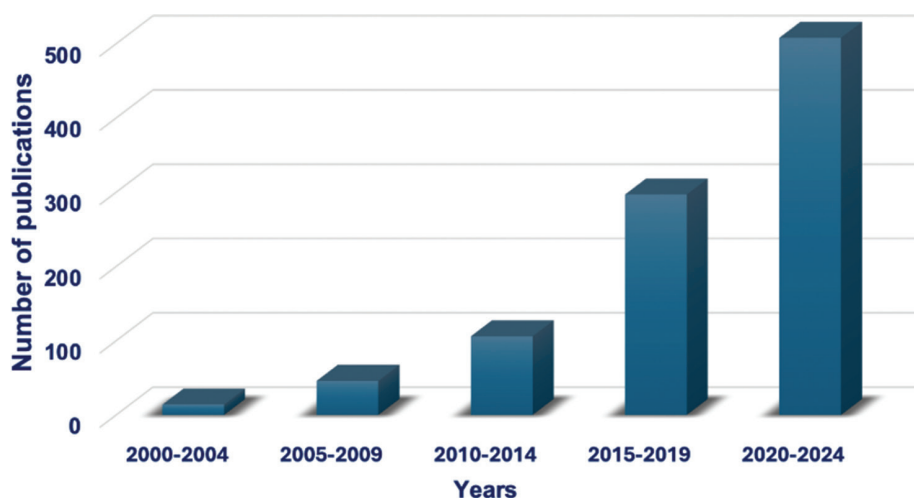


FIGURE 8.1 Overview of the emerging interest in *Moringa oleifera* for water treatment applications (2000–2024). (Source: Web of Science data base.)

Globally, researchers have identified up to 14 different species of *Moringa* [4], all of which yield seeds produced in pods. The length of these pods varies significantly, ranging from 150 to 1,200 mm, depending on the specific species and the geographic location where they are grown. The quality of these seeds can vary considerably, even between pods of the same length. Individual seeds have been shown to vary in weight from 150 to 300 mg. However, on average a single *M. oleifera* tree can produce around 2,000 seeds per year. This quantity of seeds would be sufficient to treat approximately 6,000 L of water, assuming a dosage of 50 mg per litre. Through cultivation and optimization techniques, the seed yield of *M. oleifera* trees can be increased by a factor of 5 to 10, resulting in a production of 10,000–20,000 seeds per year. This increased yield would allow up to 60,000 L of water per year to be treated with the *Moringa*-based coagulant. It is estimated that a single *M. oleifera* tree can be grown in a rural village to produce enough seeds to provide water purification for four families for a year, assuming a daily water consumption of 20 L per person. This versatile tree species is commonly found in semiarid, tropical and subtropical areas, including the Indian subcontinent, South and Central America, Africa, and Southeast Asia. As such, the tree's coagulation properties represent a pragmatic and promising option for providing access to safe drinking water in rural communities across the developing world. This alignment with the objectives of the Sustainable Development Goals (SDGs) and their emphasis on '*sustainable water management*' highlights the significant potential of the tree. Within this framework, the objective of this chapter is to assess the potential of MOC as a sustainable and accessible alternative to conventional chemical coagulants, particularly in regions with limited access to traditional water treatment methods. Additionally, it seeks to identify knowledge gaps and future research directions to further explore the applications and optimization of MO-based coagulants for comprehensive water purification solutions.

8.2 COMMON APPLICATIONS OF *MORINGA OLEIFERA*

Moringa oleifera is a versatile tree that provides a wide range of benefits, including medicinal, nutritional and industrial applications. The significance of MO has been highlighted by numerous authors in several different domains, including food, animal feed, pharmacology and cosmetics. Also, this plant is a widely recognized medicinal plant in the traditional folkloric practices of Africa and Asia. It has been used

TABLE 8.1 Application of *Moringa oleifera* in Different Industrial Areas [9–12]

SECTORS	BENEFITS
Water cleaning	• MOS powder is a natural flocculant that can remove a significant portion of colloidal matter and bacteria from cloudy water. • Certain plant seeds contain a polyelectrolyte that enables the sedimentation of suspended particles, making the seeds a potent coagulant for treating river water with high solid content.
Manufacturing	• Moringa oil is commonly used as a lubricant in fine machinery, such as in the watchmaking industry. • The oil's pigments or other chemical constituents could be extracted and used as a natural dye. • The oil may provide beneficial qualities for rope manufacturing, such as water resistance or pliability.
Cosmetic	• Skin-conditioning or emollient properties. • Ability to blend well with other cosmetic ingredients. • Potential for use as a carrier or base oil for fragrance compounds. • Potential therapeutic or skin-beneficial effects.
Pharmacological & medicinal	• Moringa leaves, seeds, and bark have demonstrated antimicrobial activity against a range of bacteria, fungi and viruses. • Moringa is rich in antioxidant compounds, including vitamins, carotenoids and polyphenols. • Compounds in Moringa, such as isothiocyanates and flavonoids, have been shown to have anti-inflammatory and pain-relieving (analgesic) properties.

to treat a variety of ailments, including ulcers, wounds, inflammation, heart problems, cancer, stroke, obesity, anaemia, and liver damage [5]. Furthermore, traditional Indian Ayurvedic medicine acknowledges the extensive therapeutic potential of MO, stating that it can prevent up to 300 different diseases. The leaves of the plant are exploited for both preventive and curative purposes [6]. Furthermore, a study conducted in India has indicated that MO is one of the species utilized by traditional Siddha healers [7]. Additionally, the ancient Egyptians were known to use MO oil for its cosmetic properties on the skin [8]. The diverse applications and benefits of MO have been well documented in the literature. Table 8.1 provides a summary of the famous and wide-ranging uses of this versatile plant.

8.3 MORINGA OLEIFERA SEEDS FOR WATER TREATMENT AS COAGULANT

Several studies have examined the performance of MO seeds as an alternative coagulant for water treatment. Earlier studies have recommended the use of *M. oleifera* seed extracts as coagulants, particularly in African and South Asian regions where the plant is native and readily available. In their study Ndacigengesere and Narasiah investigated the efficacy of water-extracted MO coagulant as a primary coagulant, reporting turbidity removal rates of up to 80%–99% for both raw and synthetic turbid waters in the initial phase of MOC research [13]. However, the coagulation of target materials has been found to present a greater challenge for organic suspended solids, such as bacteria, algae and organic matter, compared to inorganic turbid materials, when applying MOC. In a study conducted by Margarida, the researchers sought to develop a water treatment sequence utilizing MOC in conjunction with activated carbon for the removal of *Microcystis aeruginosa* and natural organic matter through an integrated process [14]. The results demonstrated a removal efficiency exceeding 80% for *M. aeruginosa* cells from

water with chlorophyll a concentration ranging from 150 to 200 µg/L, indicative of a high algae content. The water-extracted MOC was observed to be effective in the removal of algae through a combination of coagulation/flocculation and dissolved air flotation (DAF) processes. Moreover, the efficacy of MOCs in the elimination of dyes, surfactants, as well as the metal ions has been demonstrated in several studies [15,16]. For dye removal, in a study conducted by Srivastava et al., the efficacy of MO seeds as adsorbent for the treatment of dye-contaminated water was evaluated using water containing six varying concentrations of methylene blue and methylene green. The results indicated that, under optimal conditions, MO seeds could represent a cost-effective alternative for the treatment of industrial wastewater, potentially supplanting the current chemical-based methods [17]. Meanwhile, for removal of metal ions, the researchers investigated the efficacy of MO seeds, exhibiting natural particle sizes spanning from 75 to 500 µm, in the removal of Ag(I), Cd(II), Co(II), Cu(II) and Pb(II) at a concentration of 5.0 mg/L. The researchers employed a dosage of 2 g of adsorbent, a contact time of 20 minutes, a temperature of 25°C, and a pH of 6.5. The highest efficiency was observed for Ag(I), with a range of efficacy from 28% for Co(II) to 100% for Ag(I), in the following sequence: The order of efficacy was found to be Ag(I) > Pb(II) > Cu(II) > Cd(II) > Co(II) [18]. The seeds were dried at 65°C for 24 hours and subsequently employed in the study without any additional processing [18]. Beltrán-Heredia and Sánchez-Martín evaluated the potential of MO as an adsorbent for the removal of anionic surfactants from aqueous solutions. Their study found that MO was able to achieve up to 80% removal of sodium lauryl sulphate, indicating its efficacy as a surfactant elimination agent. Interestingly, the researchers also observed that the efficiency of the removal process decreased with an increase in pH. This was explained to be due to the cationic nature of the protein extracted from MO. In contrast, the effect of temperature was found to be non-significant for the removal of the surfactant [19]. In terms of the practical application of MOCs, researchers have investigated their coagulation activity, including the direct usage of the *Moringa* seed itself, for the treatment of real surface water and wastewater. In a study conducted by Poumaye et al. [60] the researchers subjected MO seeds to a drying and transformation process, resulting in the production of a powdered form. This powder was then utilized for the clarification of surface water from the M'Poko River. The researchers achieved effective reduction of turbidity and organic matter content in the water to the required standards by using a combination of sand/coal filtration and coagulation treatment with the MOC seed powder. On another study conducted by Vieira et al. [3], the potential of MO seed as a coagulant for the biodegradation of hydrocarbons present in fuel distribution terminal effluent contaminated with diesel oil and gasoline was evaluated. A mixed culture was used for the biodegradation process, and a series of coagulation conditions were tested, including variations in seed concentration, drying temperature and drying time. The researchers compared the performance of MO seed as a coagulant to those other famous natural coagulants such as chitosan and found that the latter was a more effective coagulant than the former for the sedimentation of contaminants. Although MO seeds are frequently utilized as a natural coagulant, their efficacy is not consistently superior to that of conventional coagulants. Muyibi and co-workers observed that the residual turbidity of samples increased with a reduction in the initial turbidity at the optimal dosage of water-extracted MOC [20]. This suggests that water-extracted MOC may not be an effective coagulant for low-turbidity water, which is a potential issue for its use in drinking water treatment where raw water turbidity is typically low. Furthermore, Pereira et al. [14] identified a further challenge associated with the utilisation of MOCs, namely an elevation in organic matter, particularly the dissolved organic carbon (DOC) fraction of total organic carbon (TOC), following the coagulation/flocculation process. An increase in organic matter can result in elevated biochemical oxidation demand (BOD) and chemical oxidation demand (COD), as well as the formation of undesirable colours and odours in the treated water [21]. Beltrán-Heredia et al. [45] proposed that this rise in organic matter may be attributed to the elution of superfluous components during the extraction of the coagulation-active components from the MOC seeds. To address these challenges, there is a need to enhance the extraction method for the coagulation-active components from MO seeds or to refine the purification process for these components. Such advancements are crucial for the extensive application of MOCs, not only in drinking water treatment but also in various other water treatment procedures.

8.4 COAGULATION-ACTIVE COMPOUNDS IDENTIFICATION

Prior research has identified the active coagulant components in MO seeds (MOCs) as cationic proteins with a molecular weight range of 6–16 kDa and an isoelectric pH of 10 [22,23]. Furthermore, these active components have been proposed to be dimeric cationic peptides with an isoelectric point above 10 and a molecular mass of approximately 6.5 and 13 kDa [24,25]. However, there is a lack of consensus regarding the precise nature of the active coagulating element in MOCs. Okuda et al. proposed that the active component, extracted from an aqueous salt solution, is an organic polyelectrolyte with an unknown structure, having a molecular weight of approximately 3.0 kDa and an isoelectric value above 8 [26]. In contrast, the results presented by Ghebremichael et al. demonstrated that the active component is a cationic protein with an isoelectric point greater than 9.6 and a molecular mass less than 6.5 kDa, which contradicts the findings of Okuda [27]. These inconsistencies in the reported characteristics of the active coagulant components in MOCs highlight the need for further research to accurately identify and characterize the precise nature of the active compounds responsible for the coagulation properties of MO seeds. Although the majority of researchers concur that the active component in MO is a cationic protein, the findings presented by Okuda et al. [28] warrant further investigation, suggesting the potential involvement of additional undisclosed coagulating agents in MO. It has been observed that a number of coagulant peptides can be extracted from the seed, with the sequence of one such peptide (referred to as MO_{2.1}) having been determined [24]. The recombinant form of MO_{2.1} demonstrated effective flocculation and antimicrobial properties, rendering it a suitable agent for disinfecting heavily contaminated water. Furthermore, Suarez et al. corroborated these findings by identifying a synthetic peptide that demonstrated antibacterial activity against specific human pathogens [29].

8.5 COAGULATION MECHANISM AND FUNCTIONAL GROUPS OF *MORINGA OLEIFERA*

The utilization of Moringa as an adsorbent is significant from both environmental and economic perspectives. However, there are notable information gaps that pose a barrier to understanding the mechanistic pathways governing its water purification capabilities through adsorption. In the case of MO, it is evident that a variety of interactions can occur simultaneously, including mechanisms such as precipitation, ion exchange, complexation, hydrogen bonding, electrostatic interactions, acid-base interactions and others. Typically, a mixture of these interactions is proposed to elucidate the biosorption mechanisms of MO, similar to many other biosorbents. Subsequently, certain knowledge gaps have stimulated research efforts aimed at unravelling the surface and adsorptive properties of different components of MO (such as seeds, husks, leaves) in order to better understand its sorption mechanisms. Numerous functional groups, especially the proteins, are involved in the biosorption process of MO. Each of these functional groups has different affinities for adsorbing heavy metals/dyes and several parameters play a role in managing these preferences and affinities. Accordingly, this section of this chapter provides a comprehensive examination of the adsorption mechanisms and sites involved in this process for the removal of various toxic pollutants using different biomaterials. Various studies using MO have demonstrated through FTIR spectra the presence of functional groups such as hydroxyl (–OH), carboxylic acid (–COOH), protein (–NH₂), as well as the presence of C=C, ester (–C=O), ether (>C–O) and aromatic structures within the compound. These functional groups are involved in various mechanisms and processes during the adsorption of metals and dyes, including ion exchange, chelation, physisorption,

chemisorption, among others [30]. Regarding MO under powder form, chemisorption emerges as the primary mechanism, supported by electrostatic attraction and ion-exchange mechanisms. Furthermore, electrostatic attraction stands out as a common mechanism in the biosorption process. According to Haghseresht, the ion-exchange method is often used when porous sorbents have cation-exchange capabilities, facilitating the exchange between soluble ions such as K^+ , Na^+ , Ca^{2+} , NH_4^+ and metal ions [31]. In addition, as noted by Hegazy, functional groups such as hydroxyl (OH), C–H, C=C of alkenes and C–O of carboxylic acids play a key role in metal removal in *Moringa* seed shells [32]. Figure 8.2 depicts the electrostatic and various other potential mechanisms operating on the surface of MO. The favourable adsorption of metal ions M^{2+} is facilitated by the electrostatic attraction between a protonated hydroxyl group and the metal ion. The electrostatic properties are influenced by the presence of surface chemical groups and the pH of the solutions [33]. Active sites within these surface groups in aqueous media play a role in the capture and retention of metal species. For example, the adsorption of Pb (II) is generally influenced by the mode of interaction with the solid surface [34], the ion-exchange mechanism and the electrostatic properties between the adsorbent and the adsorbate. Furthermore, the ability of MO to remove heavy metals has highlighted the role of amino acid-metal interactions in the adsorption process [35]. In addition, the greater presence of -OH groups on the sorbent surface enhances the potential for Pb-OH ion exchange (as shown in Figure 8.2), while nitrogen and oxygen functional groups can provide numerous active adsorption sites to form robust chelation with lead ions in aqueous solutions. Typically, the positively charged contaminant species present in the aqueous environment are first attracted to the surface of (MO) or MO-based biomaterials by electrostatic forces. The metal ions or dye molecules then diffuse into the porous structure of the adsorbent and encounter various functional groups. Finally, the metal ions or dyes are bound to one of these functional groups (based on their preferences, nature and class) containing nitrogen (-N), oxygen (-O) or sulphur (-S) atoms through chelation and/or ion-exchange

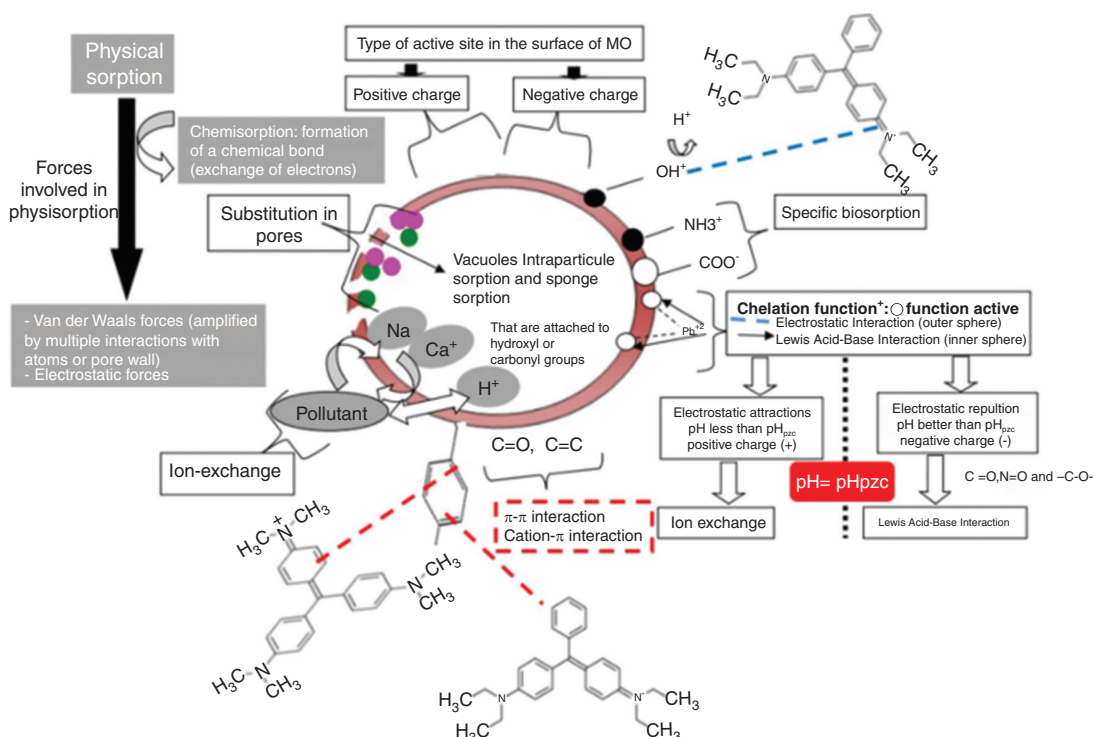


FIGURE 8.2 Various mechanisms utilized by *Moringa oleifera* in adsorption to address toxic contaminants such as CV, VB and Pb(II) in aqueous solutions [37]. (Copyright 2022, Springer.)

mechanisms, forming a stable binding structure tailored to the specific types and preferences of the metal ions, among other factors [36]. This multi-step process represents one of the potential routes by which contaminants can be adsorbed and removed by MO and MO-based biomaterials. It is important to note that these adsorption mechanisms are complex and difficult to fully understand due to their mixed nature, with multiple types of adsorption and reactions occurring simultaneously.

8.6 MORINGA OLEIFERA SEEDS FOR WATER-CONTAMINANT TREATMENT

8.6.1 Ion Metals Removal

Toxic metals from industrial sources, agricultural practices and improper waste disposal contribute to environmental pollution. Heavy metals such as arsenic, copper, cadmium, lead, mercury, nickel and zinc, with their long biological lifetimes, accumulate in the environment and pose health risks through contamination of food and water. Even at low levels, these metals can cause dermatological problems, respiratory diseases and possibly cancer. Various methods, including precipitation, oxidation/reduction, coagulation, electrocoagulation and others, are used to remove metal ions from water depending on their concentration. Recent research has investigated the utilization of MO as a natural biosorbent for the removal of toxic metals. Various studies have proposed different mechanisms for the sorption properties of MO for extracting metal ions. For instance, Kumari et al. focused on the sorption ability of MO seeds for removing arsenic from water, highlighting the role of protein/amino acid–arsenic interactions in the biosorption process [38]. Sajidu and collaborators delved into the use of MO for eliminating lead, iron, and cadmium metal ions, suggesting that both *Moringa stenopetala* and MO were effective in removing certain metal ions from water, emphasizing the pH dependency of this process for each metal [39,40]. They discussed how mechanisms such as hydrogen ion–metal cation exchange and metal hydroxide precipitation play a role in the removal process as indicated by extended X-ray absorption fine structure (EXAFS) analysis. Furthermore, Mataka and co-workers studied the application of *M. stenopetala* and MO seed powder for lead detoxification in water, with *M. stenopetala* showing higher efficacy in lead removal [41]. Additionally, Sharma investigated the potential of MO for decontaminating cadmium, identifying amino acid–cadmium interactions as key in the sorption process using FTIR spectrophotometry [42]. Subsequently, Sharma et al. investigated the competitive biosorption of Cd(II), Cr(III) and Ni(II) using SMOSP in a ternary mixture [43]. Their research revealed the selectivity order for metal ion removal as Cd(II) > Cr(III) > Ni(II). In addition, they explored the potential of regenerating used biomass for further effective reuse. Furthermore, Bhatti et al. investigated the removal of Zn(II) ions from water using native and chemically modified MO biomass [44]. Their results showed an increase in the biosorption capacity of MO biomass after pre-treatment with alkalis, acids and surfactants. In addition, Beltrán-Heredia and Sánchez-Martín investigated the efficacy of MO seed extract as a flocculant in the removal of Cu²⁺, Zn²⁺ and Ni²⁺ metal ions from surface water [45]. They found a correlation between metal removal and turbidity removal, highlighting that the interaction between turbidity and metal ions enhances the overall effectiveness of the process. Jamal et al. investigated the sorption properties of the active ingredient in MO for the removal of cadmium from contaminated water [46]. Their study involved statistical optimization to evaluate a polynomial regression model considering the effects of linear, quadratic and interaction effects of different factors. In addition, Kalibbala et al. evaluated the effectiveness of MO as a coagulant for the removal of humic matter and iron from drinking water. Their research showed promising results when MO was used in conjunction with alum as an initial treatment for water purification [47]. A summary of recent studies exploring the application of MO for the treatment of water containing heavy metal ions is presented in Table 8.2.

TABLE 8.2 Metal Ions Removal Using *Moringa oleifera* Seeds [48,49]

METAL ION	ION CONCENTRATION	COAGULANT/SORBENT DOSE	EFFICIENCY (%)
As(III)	25 mg/L	2.0 g/200 mL	60.21
Pb	7 mg/L	120 mg/L	70–89
Cd	7 mg/L	120 mg/L	44–47
Cd(II)	25 µg/mL	4 g/200 mL	85.10
Cd(II)	7 mg/L	2.5 g/100 mL	70.7
Ni(II)	4 mg/L	2 g/50 mL	90
Fluoride	5 mg/L	1 g/L	89
Fe	7 mg/L	120 mg/L	66–92

TABLE 8.3 Example of Dyes Removal Using *Moringa oleifera* Seeds

DYE	DYE CONCENTRATION (PPM)	SORBENT DOSE	EFFICIENCY (%)
Alizarin violet 3R	100	62.86 mg/L	95
Carmine indigo	100	315 mg/L	80
Congo red	20	25 mg/L	98
Congo red	25	1–4 g	98.52
Methylene blue	25	1–4 g	90.27

8.6.2 Dyes Removal

In recent years, there has been a growing focus on the use of natural biological adsorbents, or biomaterials derived from agricultural sources, as an alternative and cost-effective technology for pollutant removal. In this context, researchers have been investigating the potential of MO as an interesting natural coagulant for the removal of dyes from aqueous solutions. For instance, Marandi investigated the use of MO seeds as a natural adsorbent for the removal of orange 7 dye from wastewater [50]. Their results indicated that shelled MO seeds could be successfully used as a viable, cost-effective and pre-treatment approach in advanced wastewater treatment technologies. Further, Srivastava et al. evaluated the potential of MO seeds as a sorbent for the treatment of water containing varying concentrations of methylene blue and methylene green dyes [51]. Their study concluded that MO seeds could be applied for the treatment of industrial wastewater in a cost-effective manner, potentially replacing existing chemical-based procedures. More recently, Kumar investigated the biosorption characteristics of shelled MO seeds (SMOS) for the removal of methylene blue and Congo red dyes from aqueous systems [52]. The researchers reported the applicability of a single-layer artificial neural network (ANN) model for simulating the process and predicting the removal efficiency of SMOS for dye removal. These studies collectively demonstrate the potential of MO as a natural, sustainable and cost-effective adsorbent for the remediation of dye-contaminated water and wastewater. A summary of the key findings from these studies on the removal of dyes using MO is provided in Table 8.3.

8.6.3 Surfactant Removal

Surfactant compounds are considered one of the most hazardous and ubiquitous contaminants in water bodies, posing a significant threat to aquatic flora and fauna. The development of cost-effective and easily applicable methods for the removal of surfactants remains a critical challenge that has attracted the interest of various researchers. In this context, the ability of MO to remediate different anionic surfactants from wastewater has been investigated, with promising results reported. Heredia and Martín evaluated

the potential of MO as an anionic surfactant removal agent in aqueous solutions [53]. They observed an 80% removal of sodium lauryl sulphate, indicating the effectiveness of MO for surfactant removal. However, the efficiency of the process was found to decrease with increasing pH, which was attributed to the cationic nature of the protein extracted from MO. Conversely, the effect of temperature on surfactant removal was not found to be significant. Subsequently, the same team investigated the ability of MO seed extract to remove sodium lauryl sulphate from contaminated surface water [54]. Their jar tests demonstrated the high effectiveness of MO in surfactant removal, achieving rapid removal with relatively low coagulant doses. Additionally, they observed that the process efficiency escalated with increasing initial surfactant concentration. Furthermore, Heredia and her team chose polyoxyethelene (3.5) SLES, a long-chain anionic detergent, as a representative compound to evaluate the effectiveness of MO in removing surfactants from industrial effluents, particularly those from the laundry industry [55]. They explored the impact of different process parameters on the coagulation process and used statistical design of experiments to determine the optimal combinations for these process parameters. Subsequently, they elucidated the coagulation phenomenon using theoretical models before initiating a pilot plant. These studies collectively demonstrate the potential of MO as a cost-effective and efficient adsorbent for the removal of anionic surfactants from contaminated water and wastewater streams, highlighting its promise as a sustainable and environmentally friendly solution to this pressing environmental challenge.

8.6.4 Drinking Water

The clarification of suspended particles, or turbidity, and disinfection of water is crucial for making it fit for human consumption. Raw water drawn for drinking can become highly turbid due to the addition of solid particles, organic and inorganic compounds, and various microorganisms. This increased turbidity can adversely affect aquatic ecosystems and food chains, and the consumption of highly turbid water can pose health risks. Coagulation has been identified as an effective technique for turbidity removal, but in developing countries, the use of imported chemical coagulants like alum can be problematic. MO seeds have gained significant interest as a natural, locally available coagulant that can effectively remove turbidity. The turbid water-clarifying properties of MO seeds were first reported by Jahn, who observed Sudanese women using the seeds to clarify the turbid waters of the Nile River [56]. This observation sparked a sudden surge of interest among researchers, and since then, MO has been extensively studied as both a coagulant and a disinfectant for water treatment. Studies have consistently reported impressive turbidity reduction rates of 92%–99% when using MO seeds as a natural coagulant. The cationic nature of the seed components allows them to effectively coagulate and settle suspended particles, thereby clarifying the turbid water. However, it is important to use the optimum dose of the MO coagulant, as excessive dosages can lead to charge reversal and restabilization of the particles, resulting in increased residual turbidity. On the other hand, Water disinfection is a critical step in ensuring the safety and potability of water. The two most commonly used chemical additives for water disinfection are chlorine and chloramine. However, these chemical disinfectants can have undesirable side effects, such as the formation of carcinogenic disinfection by-products. In this context, MO seeds have emerged as an environmentally friendly substitute for the widely used chemical disinfectants. Eilert isolated an active antimicrobial agent from the seeds of MO, known as α -L-rhamnosyloxy-benzyl isothiocyanate [57]. Madsen et al. observed impressive results when using MO seed material as a coagulant and disinfectant while treating water from Sudan [58]. Their study reported 80%–99.5% turbidity removal and 90%–99.99% bacterial reduction within the first 1–2 hours of treatment, using the traditional water purification method used in Sudan. Moreover, Suarez et al. identified and characterized one of the cationic polypeptides derived from MO seeds [59]. This cationic seed-derived protein was found to have dual functionality – it could efficiently coagulate suspended particles in water, facilitating their sedimentation and removal, thereby helping to clarify the water. Importantly, this cationic polypeptide was also found to have strong antimicrobial activity. It was able to effectively purify water from several waterborne human pathogens. In another study, Poumaye et al. investigated the use of dried MO powder for the clarification of surface water in the

M'Poko River [60]. They used a factorial design approach to determine the importance of different factors and their interaction effects. The optimization process confirmed the effective coagulant properties of MO for water clarification. A significant reduction in turbidity was observed after treatment with MO, which was further reduced by subsequent filtration. In addition, clarification with MO resulted in the significant elimination of various microorganisms, with a 62% reduction in *Streptococci*, 95% reduction in *Clostridium* and 47% reduction in *Escherichia coli*. Sanchez et al. further optimized various parameters to improve the efficacy of the flocculation process using MO seed extract for water clarification. They found that the coagulation process was slightly enhanced in acidic pH conditions, and the optimum stirring rate was identified as 80 rpm. Importantly, these optimized conditions also resulted in significant reductions in microbial colonies. Even up to 72 hours of treatment, no significant regrowth of microorganisms was detected in the treated water [61].

8.7 COST OF *MORINGA OLEIFERA* SEEDS USED AS COAGULANT

As per Sutherland et al. cost analysis in 1993, the price of MO seeds for water treatment was MK 75 per 1,000 m³ water treated, while alum and soda ash cost MK 501 for a similar volume [62]. Considering a mature tree produces around 3 kg of seed kernel and treating 30,000 L of water with a 100 mg/L dose, a single tree could treat the specified amount. With a tree spacing of approximately 3 m, harvesting mature trees from 1 ha (around 3,000 kg) could effectively treat 30,000 m³ of water based on these estimations. Moreover, Sutherland et al. highlighted that the cost benefits of using MO for water treatment are particularly advantageous in African countries, where the press cake (a by-product of oil extraction) is readily available at essentially no cost. This makes MO a very cost-effective solution in those regions. However, cost dynamics can vary in different parts of the world. For example, in Malaysia, the cost of growing 1 kg of MO was estimated to be around 2\$ US, which is twice the cost of using alum as a coagulant. Similarly, in Botswana, the cost of 1 kg of MO seed was reported to be approximately 27\$ US. Yarahmadi et al. further investigated the cost situation in southern Iran, where the cultivation cost of 1 kg of MO seeds was estimated at 2\$ US [63]. This was still higher than the production cost of alum and polyaluminium chloride in the region. A study by Arnoldsson suggests that the amount of land required to produce the necessary MO seeds is not entirely unrealistic, especially for small- to medium-sized water treatment systems in rural areas [64]. In addition, the transport costs of imported chemical coagulants, such as aluminium sulphate, could be significantly reduced if they were replaced by locally sourced MO. However, additional investment would be required to store, grind and mix the MO seeds to produce the treatment extract. To minimize these transport and storage costs, it was suggested that the MO extract should be prepared on site at the water treatment site. In addition, as the MO extract can lose its coagulating and disinfecting properties over time, it is important to ensure that the extract is prepared and used fresh. This requirement for on-site preparation and timely use adds some operational simplicity compared to the use of pre-packaged chemical coagulants.

8.8 CONCLUSION

Moringa oleifera is an exceptional plant that requires minimal inputs while providing substantial benefits. Its unparalleled adaptability to different ecosystems and farming systems has secured its distinctive and enduring position in the international market. This chapter comprehensive assessment of the sustainable

use of MO for water and wastewater treatment highlights its effectiveness in removing turbidity, metal ions, organic and biological contaminants from water. In particular, its ability to achieve significant contaminant removal at lower doses makes its application economically viable. Furthermore, the non-hazardous nature of its sludge negates the need to develop environmentally friendly waste management methods, while maintaining the original chemistry of the water in terms of pH, alkalinity and ionic strength. These characteristics position MO as a promising candidate for rapid and cost-effective water treatment technology. Replacing chemical coagulants with MO could significantly reduce the transport costs associated with imported chemicals and reduce the health risks associated with their use. While its coagulation efficacy mirrors that of chemical coagulants for high turbidity waters, it is less effective for low-turbidity waters. Beyond its conventional applications, MO seed extract has been investigated as a primary coagulant, coagulant or secondary coagulant (flocculant) for drinking water purification and wastewater treatment. Consequently, by harnessing its unique properties and versatile applications, MO stands as a pivotal asset in economic and commercialization strategies, particularly within the water treatment industry.

REFERENCES

1. A.W. Jayawardena, *Int. J. Environ. Climate Change*. 2021, 11, 158–168.
2. V.A. Kumar, D.R. Roshan, B. Puspendu, *J. Environ. Manag.* 2012, 93, 154–168.
3. A.T.A. Baptista, P.F. Coldebella, P.H.F. Cardines, R.G. Gomes, M.F. Vieira, R. Bergamasco, A.M.S. Vieira, *Chem. Eng. J.* 2015, 276, 166–173.
4. M. Pritchard, T. Craven, T. Mkandawire, A.S. Edmondson, J.G. O'Neill, *Phys. Chem. Earth*. 2010, 35, 798–805.
5. P.M. Aja, N. Nwachukwu, U.A. Ibiem et al., *Am. J. Phytomed. Clin. Ther.* 2014, 2, 310–321.
6. S. Ganguly, *Int. J. Res. Ayurveda Pharm.* 2013, 4, 623–625.
7. S. Mutheeswaran, P. Pandikumar, M. Chellappandian, S. Ignacimuthu, *J. Ethnopharmacol.* 2011, 137, 523–533.
8. K.T. Mahmood, T. Mugal, *J. Pharm. Sci. Res.* 2010, 2, 775.
9. M. Broin, *Free Radic Biol Med.* 2012, 52:1–5.
10. N. Kooltheat, R. Pankla Sranujit, P. Chumark, P. Potup, N. Laytragoon-Lewin, K. Usuwanthim, *Nutrients*. 2014, 6(2), 697–710.
11. J.A. William, O.B. Kwame, N.B. Baatuwuwie, *Afr. J Agric Res.* 2015, 7(45), 6082–6086.
12. O.P. Madi, S. Bourou, N. Woin, *J. Appl. Biosci.* 2012, 60, 4421–4432.
13. A. Ndacigengesere, K.S. Narasiah, *Environ Technol.* 1996, 17, 1103–1112.
14. R.T. Margarida, S.V. Serrao, C.F. Pereira, B. Rosangela, *J. Clean. Prod.* 2017, 162, 484–490.
15. J. Beltran-Heredia, J. Sanchez-Martin, A. Delgado-Regalado, C. Jurado-Bustos, *J. Hazard Mater.* 2009, 170(1), 43–50.
16. P.B. Kumar, P.S. Kumar, *Environ. Technol.* 2015, 36, 2610–2617.
17. A.S.A. Srivastava, D.M.D. Mittal, I.S.I. Sinha, I.C.I. Chakravarty, R.B. Raja, *Ann. Biol. Res.* 2011, 2(2), 227–238.
18. L.A. Araujo, C.O. Bezerra, L.F. Cusioli, M.F. Silva, L. Nishi, R.G. Gomes, R. Bergamasco, *J. Environ. Chem. Eng.* 2018, 6, 7192–7199.
19. J. Beltrán-Heredia, J. Sánchez-Martín, *J. Environ. Technol.* 2009, 30, 525–534.
20. S.A. Muyibi, M. Lilian, *Environ. Water Res.* 1995, 29, 2689–2695.
21. F.R.P. Camacho, V.S. Sousa, R. Bergamasco, M. Ribau Teixeira, *Chem. Eng. J.* 2017, 226–237.
22. H.G. Gassen, U. Gassenschmidt, K.D. Jany, B. Tauscher, S. Wolf, *Biol. Chem. Hoppe-Seyler* 1990, 371, 768.
23. U. Gassenschmidt, K.D. Jany, B. Tauscher, *Biol. Chem. Hoppe-Seyler* 1991, 372, 659.
24. U. Gassenschmidt, K.D. Jany, B. Tauscher, H. Niebergall, *Biochim. Biophys. Acta* 1995, 1243, 477.
25. A. Ndabigengesere, K.S. Narasiah, B.G. Talbot, *Water Res.* 1995, 29, 703.
26. T. Okuda, A.U. Baes, W. Nishijima, M. Okada, *Water Res.* 2001, 35, 405.
27. K.A. Ghebremichael, K.R. Gunaratna, H. Henriksson, H. Brumer, G. Dalhammar, *Water Res.* 2005, 39, 2338.
28. C.Y. Yin, *Process Biochem.* 45, 9, 2010, 1437–1444.
29. M. Suarez, M. Haenni, S. Canarelli, F. Fisch, P. Chodanowski, C. Servis, O. Michielin, R. Freitag, P. Moreillon, N. Mermoud, *Antimicrob. Agents Chemother.* 2005, 49, 3847.

30. M. Abatal, M.T. Olguin, I. Anastopoulos et al. *Coatings*. 2021, 11(5), 508.
31. F.B. Haghseresht, S. Wang, D.D. Do, *Appl Clay Sci*. 2009, 46, 369–375.
32. I. Hegazy, M.E.A. Ali, EH Zaghlool, *Appl. Water Sci*. 2021, 11, 1–14.
33. J.J. Moreno-Barbosa, C. López-Velandia, A.D.P. Maldonado, *Adsorption* 2013, pp 675–685.
34. T.F. De Oliveira, L.A. de Moraes Pinto, J.C. Marinozi Vicentini, *Environ. Prog. Sustain. Energy* 2019, 1–10.
35. S. Subramaniam, V. Nand, M. Maata, K. Koshy, *Res. J. Chem. Environ*. 2011, 15, 135–138.
36. A.A. Swelam, S.S. Sherif, A. Ibrahim Al-Azhar, *Bull Sci*. 2018, 29(2-A), 105–124.
37. A. Benettaye, M. Usman, C. Calvin, T. Adam, *Environ. Sci. Polluti. Res*. 2022, 29, 48185–48209.
38. P. Kumari, P. Sharma, S. Srivastava, M.M.J. Srivastava, *Ind. Microbiol. Biotechnol*. 2005, 32, 521.
39. S.M.I. Sajidu, E.M.T. Henry, G. Kwamdera, L. Mataka, *WIT Trans. Ecol. Environ*. 2005, 80, 251.
40. S.M.I. Sajidu, E.M.T. Henry, I. Persson, W.R.L. Masamba, D. Kayambazinthu, *Afr. J. Biotechnol*. 2006, 5, 2397.
41. L.M. Mataka, S.M.I. Sajidu, W.R.L. Masamba, J.F. Mwatseteza, *Int. J. Water Resour. Environ. Eng*. 2010, 2, 50.
42. P. Sharma, P. Kumari, M.M. Srivastava, S. Srivastava, *Bioresour. Technol*. 2006, 97, 299.
43. P. Sharma, P. Kumari, M.M. Srivastava, S. Srivastava, *Bioresour. Technol*. 2007, 98, 474.
44. H.N. Bhatti, B. Mumtaz, M.A. Hanif, R. Nadeem, *Process. Biochem. (Oxford, U.K.)* 2007, 42, 547.
45. J. Beltran-Heredia, J. Sánchez-Martín, *J. Hazard. Mater*. 2009, 164, 713.
46. P. Jamal, S.A. Muyibi, W.M. Syarif, *Med. J. Malays*. 2008, 63, 105.
47. H.M. Kalibbala, O. Wahlberg, T.J. Hawumba, *Water Sci. Technol. Water Suppl*. 2009, 9, 707.
48. V. Vardhan, C.M. Karthikeyan, *J. Int. Water Technol. J*. 2011, 1, 120.
49. T.L. Marques, V.N. Alves, L.M. Coelho, N.M.M. Coelho, *Water Sci. Technol*. 2012, 65, 1435.
50. R. Marandi, S.M.B. Sepehr, *Am. J. Environ. Eng*. 2011, 1, 1.
51. A. Srivastava, D. Mittal, I. Sinha, I. Chakravarty, R.B. Raja, *Ann. Biol. Res*. 2011, 2, 227.
52. R.R. Kumar, A. Kardam, J.K. Arora, S. Srivastava, M.M. Srivastava, *Clean Technol. Environ. Policy* 2013, 15, 73.
53. J. Beltran-Heredia, J. Sánchez-Martín, *J. Hazard. Mater*. 2009, 164, 713.
54. J. Sánchez-Martín, J. Beltrán-Heredia, *Water Pract. Technol*. 2010, 5, 1.
55. J. Beltran-Heredia, J. Sánchez-Martín, M. Barrado-Moreno, *Chem. Eng. J*. 2012, 180, 128.
56. S.A.A. Jahn, Sudanese native methods for the purification of Nile water during the flood season. In *Biological Control of Water Pollution*; Tourbier, J.T., Pierson, R.W., Eds.; University of Pennsylvania Press: Philadelphia, PA, 1976; pp. 95–106.
57. U. Eilert, B. Wolters, A. Nahrstedt, *Planta Med*. 1981, 42, 55.
58. M. Madsen, J. Schlundt, E.F.J. Omer, *Trop. Med. Hyg*. 1987, 90, 101.
59. M. Suarez, J.M. Entenza, C. Doerries, E. Meyer, L. Bourquin, J. Sutherland, I. Marison, P. Moreillon, N. Mermod, *Biotechnol. Bioeng*. 2003, 81, 13.
60. N. Poumaye, J. Mabingui, P. Lutgen, M. Bigan, *Chem. Eng. Res. Des*. 2012, 90, 2346.
61. J. Sanchez-Martín, J. Beltrán-Heredia, J.A. Peres, *Braz. J. Chem. Eng*. 2012, 29, 495.
62. J.P. Sutherland, G.K. Folkard, M.A. Mtawali, W.D. Grant, *Moringa oleifera* as a natural coagulant. *Proceedings of the 20th WEDC Conference*, Colombo, Sri Lanka, 1994; pp. 297–299.
63. M. Yarahmadi, M. Hossieni, B. Bina, M.H. Mahmoudian, A. Naimabadie, A. Shahsavani, *World Appl. Sci. J*. 2009, 7, 962.
64. E. Arnoldsson, M. Bergman, N. Matsinhe, K.M. Persson, *VATTEN* 2008, 64, 137.

Heavy Metal Removal Using Phytoremediation Approaches

9

Priyadarshini Pillai, Chinappan Balaji Ayyanar, Veluswamy Rinusuba, and Gayathri

9.1 INTRODUCTION

The phrases “bioremediation,” “botanical remediation,” and “green remediation” are all included in the 1991 coinage of “phytoremediation” (Salt et al., 1998). According to Assunção et al. (2001), it entails using plants to remove both organic and inorganic materials from contaminated environments. It works quickly in areas with light pollution, but less effectively in areas with severe pollution (Lasat, 2002). Some plant species, especially those that are metal hyper-accumulators and wild types, are very effective at eliminating contaminants at much higher rates than are cultivated plants (Boyajian & Carreira, 1997). This environmentally friendly phytoremediation technique makes it easier to reuse land and doesn’t require any specific equipment (Pilon-Smits, 2005). Its efficacy is greatly influenced by variables including climate and root depth (Clemens et al., 2002).

For plants to successfully extract pollutants, the soil must meet certain requirements. Specifically, the pH levels of the soil should be between 5.8 and 6.5 to maximize nutrient uptake (Gohre & Paszkowski, 2006). The process of pollutant absorption and buildup by plants is depicted in Figure 9.1. According to Salt, Smith, and Raskin (1998), there are several methods that fall under the umbrella of phytoremediation, such as phytoextraction, phytoaccumulation, phytotransformation, phytodegradation, phytostabilization, rhizodegradation, rhizofiltration, mycoremediation, and mycofiltration. By leveraging the interaction between plant roots and related bacteria to treat soils containing high quantities of organic pollutants, it entails using plants to remediate contaminated soils, waterways, and even groundwater (Raskin, Smith, & Salt, 1997).

Human-caused contaminants are a serious concern to both human health and wildlife. Contaminants can cause biomagnification, a process wherein they accumulate at higher trophic levels, even at very low levels in the environment. Inorganic pollutants, such as metals, are frequently

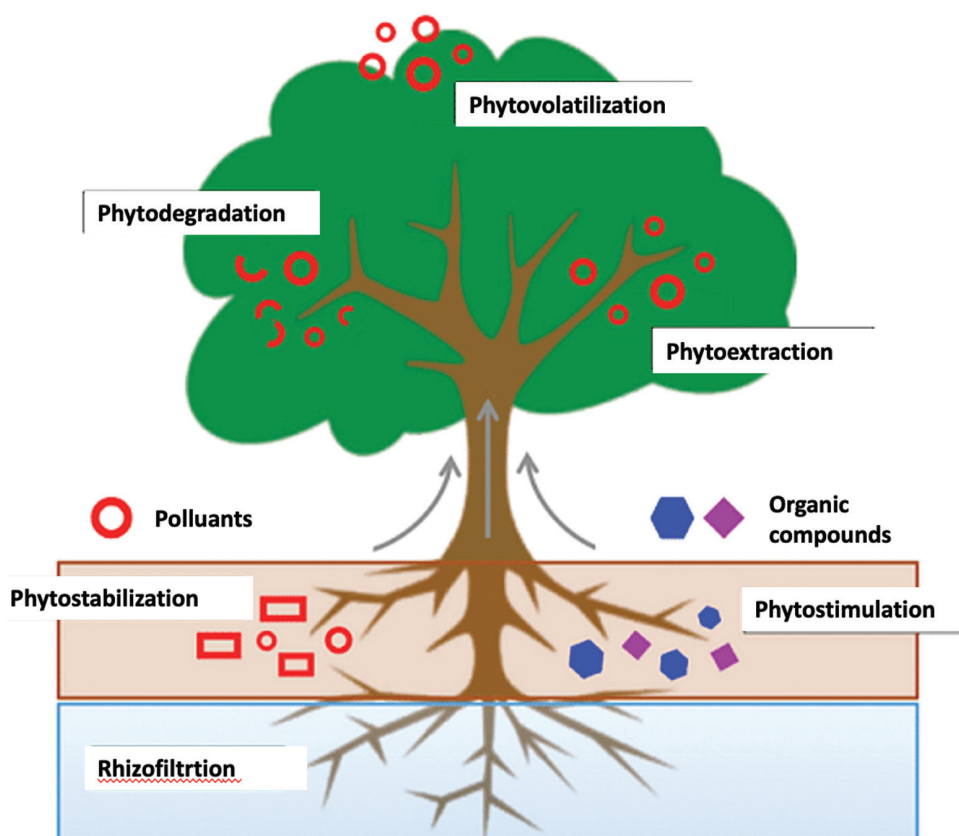


FIGURE 9.1 Phytoremediation techniques. (Source: Shikha and Singh, 2021.)

found in soil at low concentrations, but organic contaminants are usually alien to plants. Plant growth depends on essential micronutrients like zinc (Zn), cobalt (Co), copper (Cu), iron (Fe), molybdenum (Mo), manganese (Mn), and copper (Fe). Nonessential metals, however, can have harmful effects on plants even at low concentrations. These include arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hg), nickel (Ni), lead (Pb), selenium (Se), uranium (U), vanadium (V), and wolfram (W) (Kumar et al., 2023).

Plants mainly absorb metal through certain transporters found on the root cell membrane. The Fe-regulated transporter (IRT1), for example, is capable of transporting additional metals in addition to Fe when Fe availability is insufficient. Other cell membrane transporters, including phosphorus transporters, may unintentionally allow nonessential metals to enter plants and facilitate arsenic (AsO_3) uptake (Lasat, 2002; Clemens et al., 2002). Utilizing plants and related soil microbes to reduce pollutant concentrations or toxicity is known as phytoremediation, and it has become a popular and affordable method of environmental cleanup (Pilon-Smits, 2005; Raskin et al., 1997). It can handle a variety of pollutants in a variety of settings and provides a less harmful substitute for conventional engineering techniques. However, because phytoremediation is limited to the plant root zone, it might not be appropriate in situations where contaminant concentrations are higher than what plants can tolerate (Assunção et al., 2001; Gohre and Paszkowski, 2006). Diverse environmental scenarios and pollutant types are accommodated by various phytoremediation processes, such as *in situ* stabilization, degradation, volatilization, and extraction (Salt et al., 1998; Boyajian and Carreira, 1997) (Figure 9.2; Table 9.1).

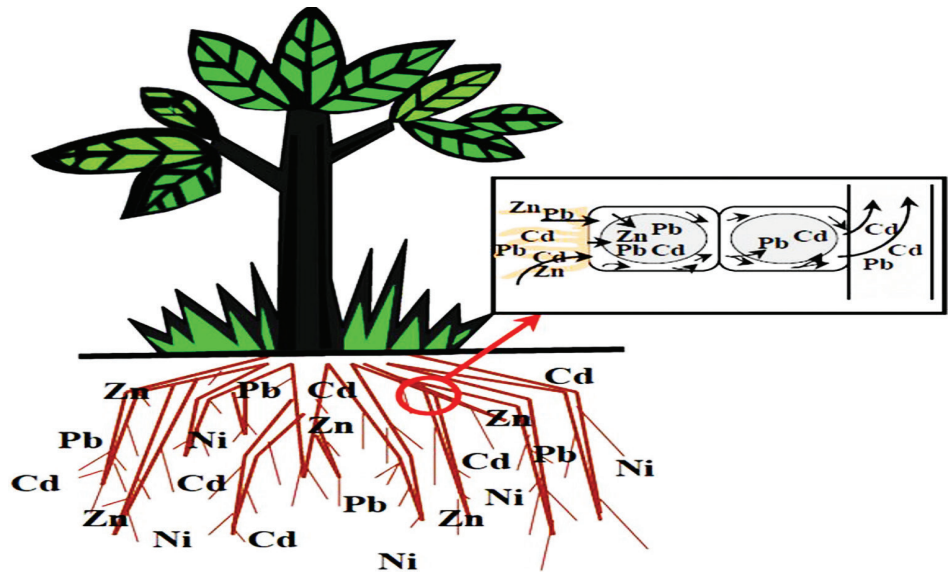


FIGURE 9.2 Heavy metal absorption and accumulation in root and shoot of the plant. (Source: Mersin, 2010.)

TABLE 9.1 Comparison between Phytoremediation Technologies

TECHNOLOGY	ACTION ON CONTAMINANTS	MAIN TYPE OF CONTAMINANTS	VEGETATION
Phytostabilization	Retained <i>in situ</i>	Organics and metals	Cover maintained
Phytodegradation	Attenuated <i>in situ</i>	Organics	Cover maintained
Phytovolatilization	Removed	Organics and metals	Cover maintained
Phytoextraction	Removed	Metals	Harvested repeatedly

Source: Salt et al. (1998).

9.2 HOW DOES PHYTOREMEDIATION WORK?

According to Harper et al. (1999), there are three steps in the process of a plant-absorbing nutrient elements: the nutrients are transported to the root surface and root circle. Nutritional ions are absorbed by the roots. Nutrient ions are transported via the transmission branches from the roots to the required regions.

9.3 HEAVY METAL SOURCES IN SOIL AND WATER

Because heavy metals (HM) can bioaccumulate and have hazardous effects on living things, contamination with HM has drawn attention from all over the world. Because of their high elemental density, HMs are usually categorized as either metals or metalloids. Differences between the two groups based on density, weight, or atomic number introduced a new criterion, stating that HMs should have an atomic density greater than 41 g/cm³, using metals like Cd, Cr, Co, Cu, Pb, Hg, and Zn as examples. In both terrestrial and aquatic ecosystems, even minute concentrations of HMs can have major negative effects.

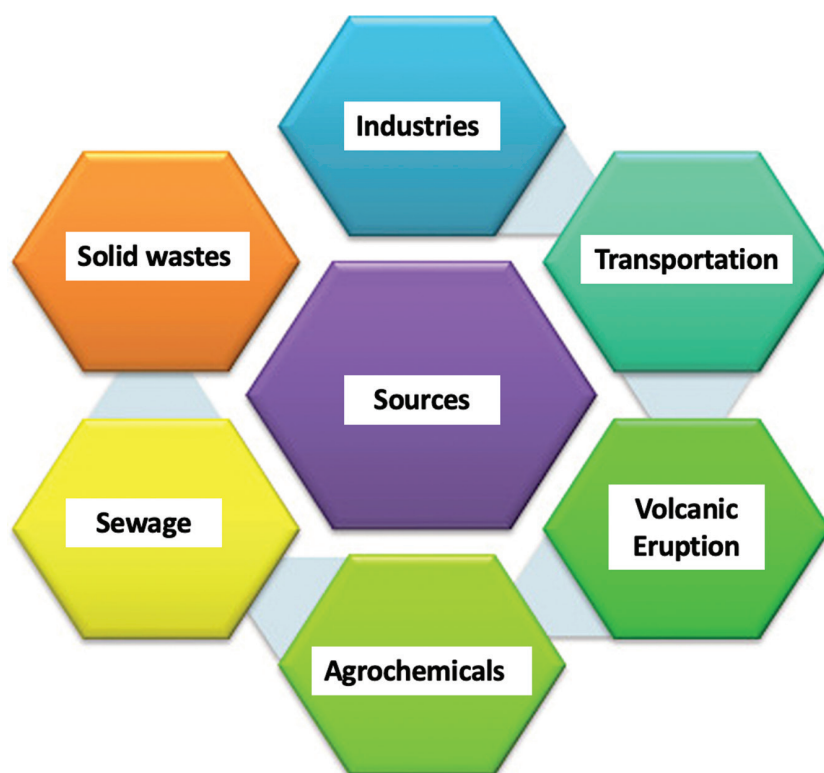


FIGURE 9.3 Different sources responsible for heavy metal accumulation in water and soil. (Source: Prodipto Bishnu et al., 2024.)

Diffuse causes of this influence could include air emissions, which have been found to be a major cause of soil and water contamination. These sources pose serious risks to both human health and ecological settings.

Volcanoes, soil erosion, rock disintegration, and other natural phenomena release HMs. Man-made activities, on the other hand, greatly increase the amount of HM pollution, including incomplete burning of fossil fuels, mineral extraction, landfilling, metal refining, manufacturing of electronic goods, production of dyes, use of agricultural chemicals, military operations, and vehicle emissions. Wastewater from mining, sewage, dyeing operations, and alloy manufacture frequently contains toxic HMs such as As, Cd, Cr, Cu, Hg, Pb, and others. Environmental pollution is primarily caused by anthropogenic behaviors rather than natural causes. Due to their high reactivity, many HMs are extremely dangerous to the environment and public health. Figure 9.3 lists the main human-caused activities that increase the levels of hazardous metals in the environment. These activities involve the introduction of metals such As, Cd, Pb, Hg, Ni, Zn, and U through mining, smelting, or agrochemical processes.

9.4 EFFECT OF HEAVY METALS ON HUMAN HEALTH

Even in small quantities, HMs can be harmful to human health. By producing free radicals, they cause oxidative stress. They can also replace essential metals in pigments and enzymes. Arsenic (As), mercury (Hg), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), tin (Sn), and zinc (Zn) are some of the most hazardous HMs. Cu and Zn are categorized as trace elements, whereas Hg, Cd, Pb, and As are deemed nonessential. The particular metal, its content, and its oxidation state all affect how hazardous HMs are

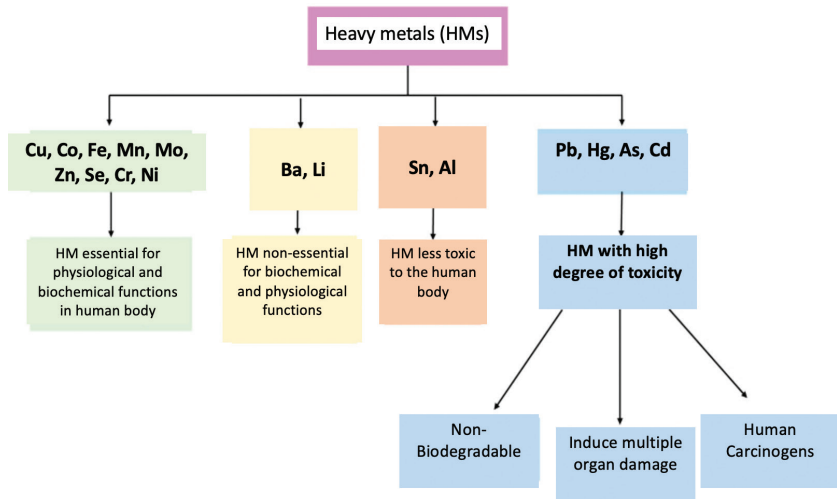


FIGURE 9.4 Classification of heavy metals based on their role in the human body. (Source: Nabulo et al. 2011.)

TABLE 9.2 Various Hazardous Impacts of Different Heavy Metals on Human Health

HEAVY METAL	RELATED HAZARDOUS EFFECTS
As	Interferes with key cellular functions in human body
Cd	Chronic anemia, mutagenic, renal failure, carcinogenic, etc.
Cr	Hair loss
Cu	Brain and kidney injury, liver cirrhosis, stomach and intestinal inflammation have all been linked to elevated levels
Hg	Anxiety, autoimmune disorders, depression, trouble with coordination, exhaustion, loss of hair, insomnia, irritability, ulcers, and brain, kidney, and lung damage are just a few of the symptoms
Ni	Nickel itch is allergic dermatitis; inhalation can cause lung, nose, and sinus cancers; throat and/or stomach cancers. Causes hair loss by being hematotoxic, neurotoxic, genotoxic, nephrotoxic, and hepatotoxic
Pb	Its poisoning causes developmental delays, decreased intelligence, learning difficulties, and balance issues in infants, as well as renal failure, cardiovascular disease
Zn	Overdosing will result in dizziness and exhaustion

to human health. Nonessential metals are among the critical contaminants that are hazardous to human health and the ecological balance, with differing levels of toxicity. These metals can have a major detrimental effect on one’s health, ranging from relatively modest levels of toxicity seen in elements like barium (Ba), lithium (Li), aluminum (Al), and tin (Sn) to highly toxic elements like lead (Pb), arsenic (As), cadmium (Cd), and mercury (Hg) (Nabulo et al., 2011). A system of HM classification based on physiological roles in the body is shown in Figure 9.4 (Table 9.2).

9.5 PLANTS USED FOR PHYTOREMEDIATION

- Lead, uranium, cesium, and strontium remediation using sunflowers (*Helianthus annuus*).
- Lead, cadmium, nickel, and zinc remediation using Indian mustard (*Brassica juncea*).
- Willow (*Salix* spp.): Organic contaminants, HMs, and petroleum hydrocarbons can all be remedied.

- Poplar (*Populus* spp.): HM, petroleum hydrocarbon, and volatile organic compound (VOC) remediation.
- Alfalfa (*Medicago sativa*): HM, chlorinated solvent, and petroleum hydrocarbon remediation.
- Pennisetum (*Pennisetum purpureum*): Organic contaminants and HM remediation.
- Ferns (*Pteris vittata*): Cleaning up soil tainted with arsenic.
- Water hyacinth (*Eichhornia crassipes*): Cleansing up water bodies of surplus nutrients, organic contaminants, and HMs.
- Duckweed (*Lemna* spp.): Removes excess nutrients, organic contaminants, and HMs from water bodies.
- Cattail (*Typha* spp.): Organic contaminants, petroleum hydrocarbons, and HMs can all be remedied in wetland habitats.
- Bamboo (*Bambusa* spp.): Remediation of soil and water for nutrients, organic contaminants, and HMs.
- Sedum (*Sedum* spp.): Cleaning up contaminated soils of organic and HM pollution.

9.6 PHYTOREMEDIATION MECHANISM

Numerous processes are used in the process and most recent developments of phytoremediation of HM-contaminated soils with the goal of immobilizing, transforming, and absorbing metals into plant tissues inside the soil matrix. An illustration shows the sections of the plant that can be harvested, mainly the leaves, and on which elements such as selenium (Se) and mercury (Hg) have successfully volatilized into forms that are not harmful. Concerns about the possible recycling of metals through leaf drop and precipitation processes, however, continue to exist. Furthermore, because conditions inside shared rhizospheres may affect metal bioavailability to surrounding plants, co-plant rhizospheric interactions influence the performance of species in metal uptake. Considering the competition between certain HMs, like copper (Cu) and zinc (Zn), as well as nickel (Ni) and cadmium (Cd), for the same membrane protein transporters, ongoing efforts entail screening plants for multi-metal hyper-accumulators (Baker and Brooks, 1989). Furthermore, this technique's future prospects include genetic engineering treatments that target the biomass, tolerance, root, leaf, and accumulation potentials of identified species. To aid potential tissue uptake, the picture depicts several HM contaminants—represented by circles and triangles—that are either immobilized or mineralized by natural plant exudation or by being supplemented with synthetic chelators (Figure 9.5).

9.7 TYPES OF PHYTOREMEDIATION

9.7.1 Phytoextraction/Phytoaccumulation

- In a process called phytoextraction, sometimes referred to as phytoaccumulation, contaminants are accumulated by plants in their roots, shoots, or above-ground leaves.
- The biomass of plants above ground is where roots concentrate components that they have taken up from the soil or water.
- Plants that have a high capacity to absorb contaminants are known as hyper-accumulators.

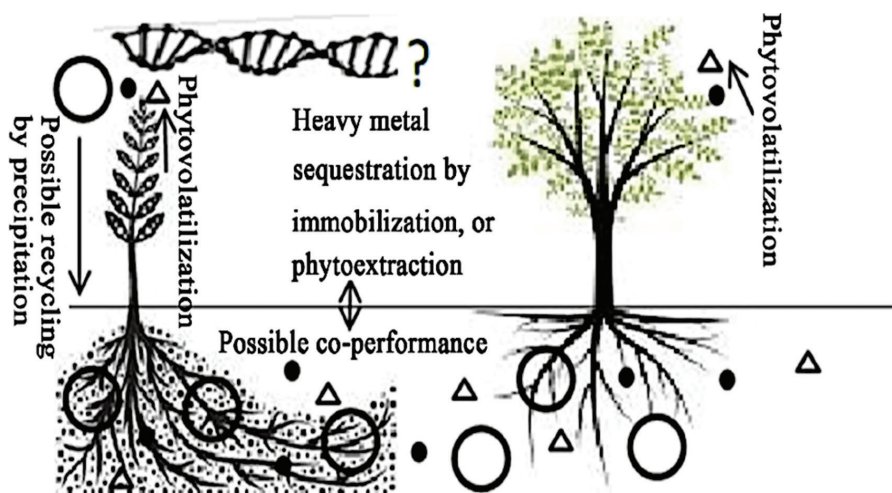


FIGURE 9.5 Mechanism of phytoremediation. (Source: Nwaichi and Dhankher, 2016.)

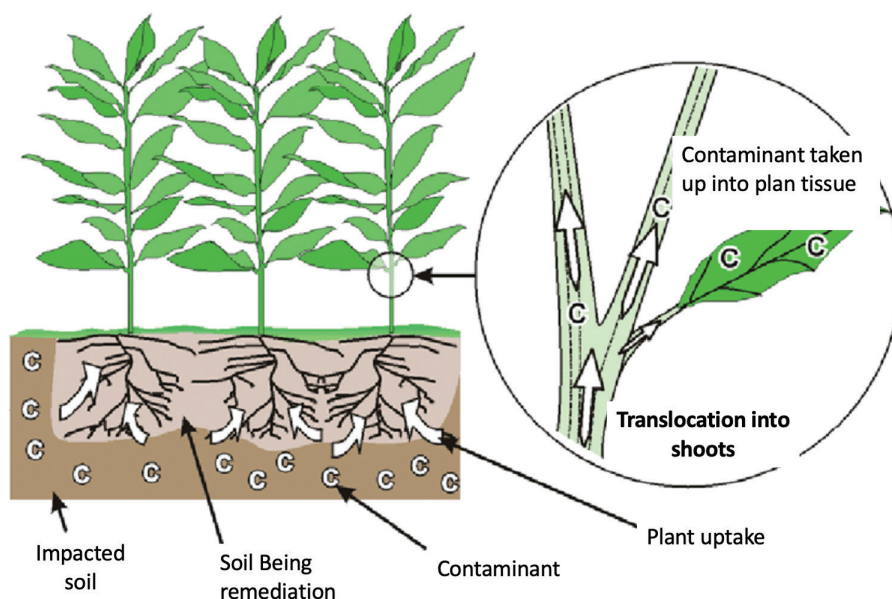


FIGURE 9.6 Phytoextraction process. This figure depicts the phytoextraction process in plants. (Source: ITRC, 2001.)

- Over the past 20 years, phytoextraction has become more and more popular all over the world, especially for the extraction of HMs and other inorganic materials.
- Compared to the originally contaminated soil or silt, contaminants are frequently concentrated in a smaller volume of plant matter at disposal.
- Even though there are usually less pollutants in the soil after harvest, cleaning up effectively usually requires several growth/harvest cycles, which ultimately results in soil remediation (Figure 9.6).

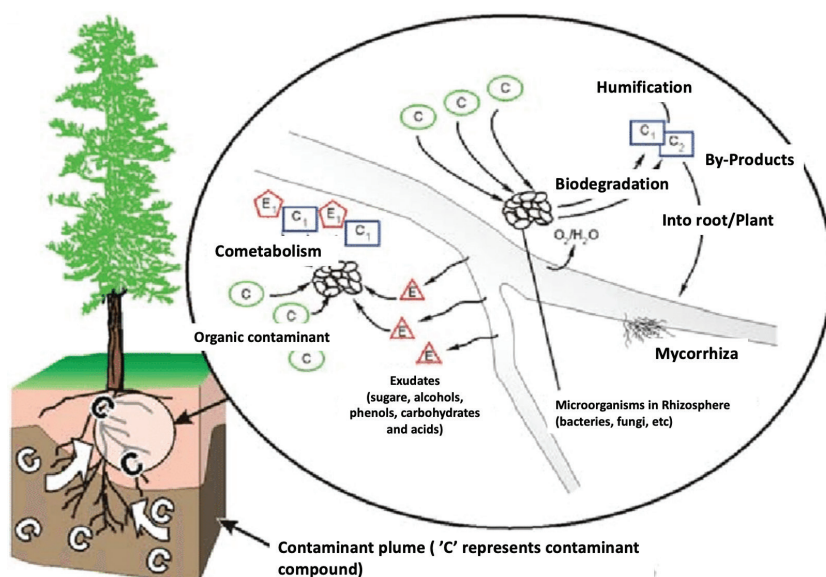


FIGURE 9.7 Phytodegradation process. This figure depicts the phytodegradation process in trees. (Source: ITRC, 2001.)

9.7.2 Phytotransformation/Phytodegradation

- Known also as phytodegradation, phytotransformation is the process by which organic contaminants found in soil, sediments, or water are changed into less dangerous and less mobile forms.
- Organic compounds are broken down by enzymes generated by plant roots, which are subsequently taken by the plant and discharged by transpiration.
- This technique works very well with methyl tert-butyl ether, trichloroethylene, and pesticides.
- Through plant metabolism, ambient chemicals undergo phytotransformation, which changes their chemical makeup and causes inactivation, destruction, or immobilization (phytostabilization).
- Organic pollutants including pesticides, explosives, solvents, industrial chemicals, and xenobiotic substances are broken down by some plants, like cannas, making them nontoxic.
- Alternatively, these chemicals may be metabolized in soil or water by bacteria that reside close to plant roots (Figure 9.7).

9.7.3 Phytostabilization

- The process of phytostabilization entails planting plants to inhibit the spread and migration of polluted soil.
- Toxins are unable to escape from an unstable mass of soil formed by leachable components that have been absorbed and bound inside the plant structure.
- Plants immobilize pollutants by attaching them to soil particles, which lessens the amount of the toxins that plants and people may absorb.
- Phytostabilization seeks to isolate pollutants in the soil close to the roots, in contrast to phytoextraction, which concentrates on building up pollutants in plant tissues.
- The risk of exposure decreases with a reduction in the bioavailability of contaminants.

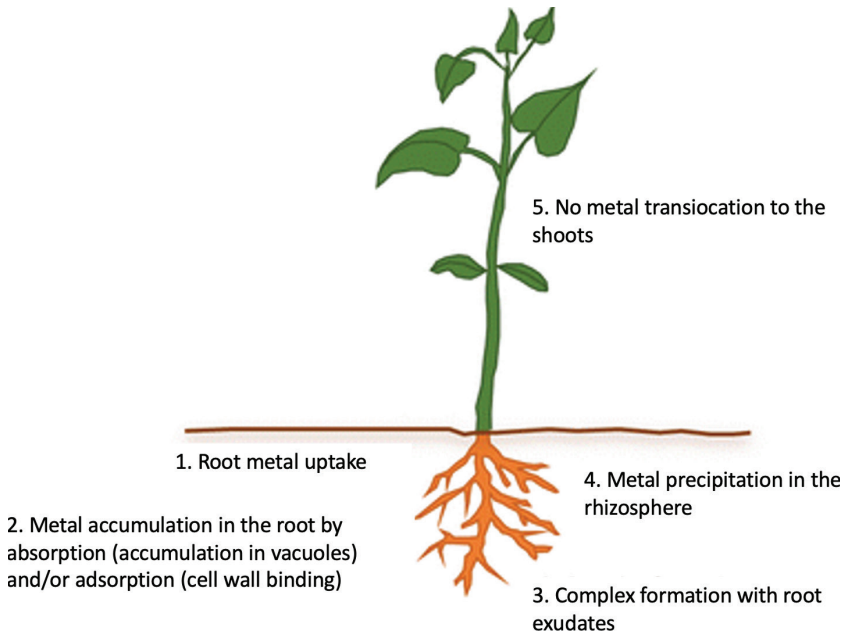


FIGURE 9.8 Process of phytostabilization. (Source: Karaca et al., 2018.)

- Additionally, plants have the ability to produce chemicals that start chemical reactions that change HM pollution into less dangerous forms.
- Stabilization lowers the bioavailability of pollutants and lessens erosion, runoff, and leaching.
- The use of a vegetative cover to stabilize and contain mining tailings is an example of phytostabilization in action (Figure 9.8).
- Rhizodegradation, sometimes called phytostimulation, is the process by which pollutants are broken down with the help of rhizosphere activity.
- The proteins and enzymes produced by plants or soil organisms, such as bacteria, yeast, and fungi, are responsible for this process.
- Some bacteria have the ability to break down dangerous pollutants, such as fuels and solvents, into innocuous byproducts.
- Naturally occurring carbon-containing substances like sugars, alcohols, and acids are released by plants. These substances provide microorganisms with extra nutrition and increase their activity.
- The potential to increase rhizodegradation efficiency is there in transgenic plants designed to interact with microorganisms more effectively.
- One area that could use improvement is the plant's innate capacity to emit compounds that encourage microbial activity (Figure 9.9).

9.7.4 Rhizofiltration

- Harmful chemicals and excess nutrients can be eliminated from water sources using rhizofiltration, a method that involves filtering water through a dense network of roots.
- Pollutants are directly absorbed by roots or are transferred to the root surface by them.
- Direct planting in the impacted region or the transportation of polluted water to approved plant locations off-site are the two most popular methods used to remediate contaminated groundwater.

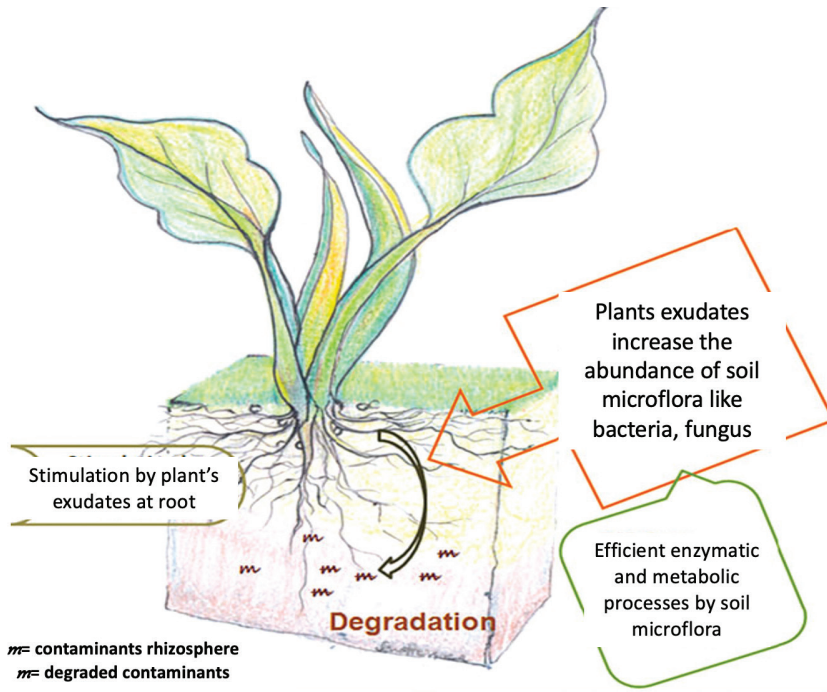


FIGURE 9.9 Process of phytostimulation where plant exudates stimulate the microflora of root zone to degrade contaminants. (Source: Datta et al., 2013.)

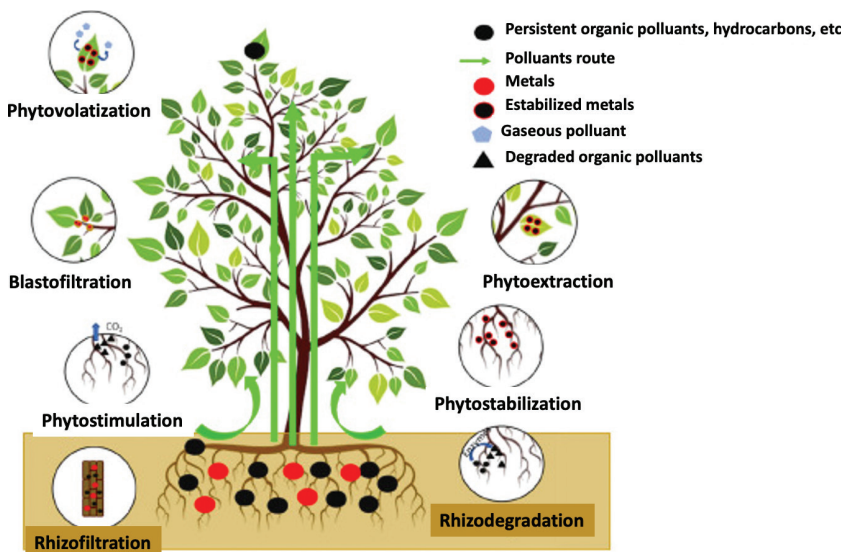


FIGURE 9.10 Process of rhizofiltration. (Source: <https://doi.org/10.1016/B978-0-12-811139-0.00012-8>.)

- For maximum effectiveness, plants are usually grown in greenhouse environments with carefully regulated circumstances.
- Rhizofiltration is used to minimize pollutants in estuary and wetland settings (Figure 9.10).

9.8 PHYTOREMEDIATION—ADVANTAGES

- **Ecologically beneficial method:** Because phytoremediation reduces pollution exposure to the environment and ecosystems, it is regarded as an environmentally beneficial method.
 - **Scalability and convenient disposal:** This method makes it easy to dispose of contaminants and may be applied on a wide scale.
 - **Erosion prevention and containment:** By stabilizing HMs, phytoremediation lowers the likelihood of contamination spread and aids in the prevention of erosion and metal leaching.
 - **Improvement of soil fertility:** Moreover, phytoremediation can improve soil fertility by enriching it with different organic components that the plants release.
-

9.9 PHYTOREMEDIATION—DISADVANTAGES

- **Relocation as opposed to removal:** In phytoremediation, dangerous HMs are relocated as opposed to being totally eliminated from the environment.
 - **Restricted root area:** The extent of phytoremediation is limited to the surface area and depth that plant roots occupy.
 - **Sluggish growth and biomass constraints:** Phytoremediation operations must be sustained over an extended period of time due to the sluggish growth rate and restricted biomass of plants.
 - **Inadequate pollutant prevention:** Leaching of pollutants into groundwater cannot be completely stopped by plant-based remediation methods.
 - **Effect on plant survival:** The survival of plants used in phytoremediation is greatly impacted by the toxicity of contaminated soil as well as the general quality of the soil.
 - **Organic binding of metals:** When HMs are absorbed by plants, they may bind to organic soil components, making it more difficult for the plant to remove the metal.
-

9.10 PHYTOREMEDIATION—APPLICATIONS

- **Soil and water:** The treatment of stable pollution in soil or aquatic environments is frequently accomplished by the use of phytoremediation.
- **Abandoned mine sites:** Remedialization of soils, water, and air is aided by initiatives to rehabilitate polychlorinated biphenyl (PCB)-contaminated sites and abandoned metal mine workings, as well as by reducing the effects of pollutants from operating coal mines.
- **Pesticides, crude oil, and derivatives:** Across the globe, phytoremediation programs have been effective in lowering the concentrations of metals, pesticides, explosives, solvents, and crude oil as well as its derivatives.
- **Hazardous waste sites:** A number of plant species, including hemp, pigweed, alpine pennycress, and mustard, have demonstrated the capacity to hyper-accumulate toxins at hazardous waste sites.

9.11 CONCLUSION

In the last ten years, there has been a significant increase in research conducted worldwide on phytoremediation as a way to deal with HM pollution in different settings. This economical and ecologically friendly technique is becoming more and more popular as a substitute for conventional remediation techniques. Concerns about biomass management and the technique's effectiveness, however, still exist. Phytoremediation is a promising solution for countries such as Nigeria, where fast development has led to an abundance of contamination sources. It is critical to evaluate changes in soil communities and their physiological profiles in addition to physical and chemical data because the goal of soil remediation is to promote biodiversity and restore ecological services. To protect and restore soils, government organizations and pertinent authorities need to vigorously enforce adherence to frequently reviewed standards, going beyond simple regulations. Additionally, it is crucial to promote phytoremediation research and increase public knowledge of its possible advantages. To pinpoint the shortcomings, achievements, and possible uses of phytoremediation technology in resolving the urgent environmental problem of HM pollution, a thorough assessment of its current state is required.

REFERENCES

- Assunção, A. G. L., Ten Bookum, W. M., Nelissen, H. J. M., Vooijs, R., Schat, H., Ernst, W. H. O., & Aarts, M. G. M. (2001). Elevated expression of metal transporter genes in three accessions of the metal hyperaccumulator *Thlaspi caerulescens*. *Plant, Cell & Environment*, 24(2), 217–226. doi:10.1111/j.1365-3040.2001.00666.x.
- Baker, A. J. M., & Brooks, R. R. (1989). Terrestrial higher plants which hyperaccumulate metallic elements: A review of their distribution, ecology and phytochemistry. *Biorecovery*, 1, 81–126.
- Boyajian, G. E., & Carreira, L. H. (1997). Phytoremediation: A clean transition from laboratory to marketplace. *Nature Biotechnology*, 15(2), 127–128. doi:10.1038/nbt0297-127.
- Clemens, S., Palmgren, M. P., & Krämer, U. (2002). A long way ahead: Understanding and engineering plant metal accumulation. *Trends in Plant Science*, 7(7), 309–315. doi:10.1016/S1360-1385(02)02295-1.
- Datta, S., Chatterjee, S., Mitra, A., & Veer, V. (2013). Phytoremediation protocols: An overview. doi:10.1007/978-3-642-35564-6_1.
- Gohre, V. & Paszkowski, U. (2006). Contribution of the arbuscular mycorrhizal symbiosis to heavy metal phytoremediation. *Planta* 223, 1115–1122. doi:10.1007/s00425-006-0225-0.
- Gupta, N., & Singh, A. (2023). Recent trends in phytoremediation technologies for heavy metal contaminated sites in India. *International Journal of Phytoremediation*, 25(3), 283–295.
- Karaca, Ö., & Cameselle, C., & Reddy, K. (2018). Mine tailing disposal sites: Contamination problems, remedial options and phytocaps for sustainable remediation. *Reviews in Environmental Science and Bio/Technology*, 17. doi:10.1007/s11157-017-9453-y.
- Kumar, S., Sharma, P., & Singh, M. (2023). Potential of indigenous plants for phytoremediation of heavy metal contaminated soils in India: A Review. *Environmental Science and Pollution Research*, 30(2), 1721–1735.
- Lasat, M. M. (2002). Phytoextraction of toxic metals: A review of biological mechanisms. *Journal of Environmental Quality*, 31, 109–120. doi:10.2134/jeq2002.0109.
- Meers, E. et al. (2008). Chemically assisted phytoextraction: A review of potentially soil amendments for increasing plant uptake of heavy metals. *International Journal of Phytoremediation*, 10, 390–414. doi:10.1080/15226510802100515.
- Mishra, S., Singh, V., & Singh, R. (2023). Phytoremediation potential of Indian plant species for heavy metal contaminated sites: A comprehensive review. *Journal of Environmental Management*, 302, 113751.
- Nabulo, G., Black, C., & Young, S. (2011). Trace metal uptake by tropical vegetables grown on soil amended with urban sewage sludge. *Environmental Pollution*, 159:368–376. doi:10.1016/j.envpol.2010.11.007.
- Patel, S., Sharma, A., & Pandey, A. (2023). Application of native plants in phytoremediation of heavy metal contaminated sites in India: A review. *Ecological Engineering*, 182, 106058.

- Pilon-Smits, E. (2005). Phytoremediation. *Annual Review of Plant Biology*, 56, 15–39.
- Raskin, I., Smith, R. D., & Salt, D. E. (1997). Phytoremediation of metals using plants to remove pollutants from the environment. *Current Opinion in Biotechnology*, 8(2), 221–226.
- Salt, D. E., Smith, R. D., & Raskin, I. (1998). Phytoremediation. *Annual Review of Plant Physiology and Plant Molecular Biology*, 49, 643–668.
- Shikha, D., & Singh, P. K. (2021). In situ phytoremediation of heavy metal–contaminated soil and groundwater: A green inventive approach. *Environmental Science and Pollution Research*, 28, 4104–4124. doi:10.1007/s11356-020-11600-7.

Biological Wastewater Treatment

10

Fundamentals and Recent Development in Nutrient Removal

Priyadarshini Pillai, Chinappan Balaji Ayyanar,
Veluswamy Rinusuba, and Gayathri

10.1 INTRODUCTION

Industrial activity has increased significantly in the contemporary era, which has resulted in the production of large volumes of waste, including wastewater. The potential for reusing this effluent is becoming more widely acknowledged, especially in light of the paucity of potable water in many areas. However, its disposal poses serious environmental challenges. New and persistent waste kinds have been produced in proportion to the introduction of new products and manufacturing processes. Conventional wastewater treatment techniques might find it difficult to effectively remove these pollutants, which would exacerbate the already urgent problem of water scarcity. Therefore, to reduce the burden on the environment, it is imperative that novel wastewater treatment techniques be developed. Many different technologies have been created for the treatment of both organic and inorganic wastewater. These technologies include chemical, physical, and biological approaches (Gupta and Bux, 2019). Membranes are now essential in many industries, especially when it comes to treating fatty and greasy industrial water, where notable improvements in filtration methods have been noted. Technologies based on microalgae present a viable option for carbon fixation and wastewater remediation. They work especially well on organic matter and heavy metals, as well as inorganic elements like phosphorus and nitrogen. Moreover, microalgae activities can produce biomass that is highly valuable and carry a low risk of secondary contamination. Another innovative approach to wastewater treatment is microbial fuel cells (MFCs), which harness microbial activity to generate electricity while simultaneously treating wastewater.

They use the organic and inorganic substances found in wastewater to produce energy through the bioelectrical catalytic activity of microorganisms. MFC technology helps clean wastewater in a single configuration in addition to enabling energy recovery.

10.2 WASTEWATER CONTAMINANTS

10.2.1 Nitrogen and Phosphorus

In wastewater effluents, nitrogen and phosphorus are the main eutrophic nutrients. According to studies, the percentage of streams with medium to high phosphorus and nitrogen content is around 47% and 53%, respectively. Ammonia and organic nitrogen are the most common types of nitrogen found in untreated wastewater, whereas phosphate can take the form of soluble orthophosphate ions, organically bound phosphate, or various forms of phosphorus and oxygen.

10.2.1.1 Effects

Algal blooms are the main indicator of eutrophication, which lowers the dissolved oxygen content of water bodies. The death of aquatic life, turbidity in the water, and a major decline in attractive flora and fauna are all possible outcomes of this oxygen shortage. Additionally, eutrophication raises the need for chlorine in water disinfection, which may raise the risk of cancer. Overproliferation of nutrients in wastewater effluents can encourage pathogenic microbes such as *Pfisteria*, leading to a range of health problems, including headaches, gastrointestinal complaints, and irritation of the eyes and respiratory tract. In newborns and other vulnerable people, elevated nitrate levels over the maximum contaminant threshold of 10 mg/L can cause methemoglobinemia, or “blue baby disease,” in which nitrate is transformed into nitrite in the digestive tract and attacks hemoglobin.

10.2.2 Heavy Metals

Even at low quantities, heavy metals offer a serious risk of contamination due to their toxicity and high atomic mass. Cadmium (Cd), chromium (Cr), nickel (Ni), mercury (Hg), lead (Pb), manganese (Mn), copper (Cu), zinc (Zn), and mercury (Hg) are examples of common poisonous heavy metals. The main industrial processes that cause heavy metal pollution in wastewater are mining, metallurgy, and electroplating.

10.2.2.1 Effects

In particular, newborns and unborn children are at risk for experiencing stomach pains, skin irritation, vomiting, nausea, anemia, and respiratory problems as a result of zinc poisoning. Exposure to lead can impede the synthesis of hemoglobin, resulting in anemia and permanent health consequences, such as a persistent loss in kidney function. Compared to inorganic forms, organic forms of mercury are more poisonous to aquatic life, and even minimal amounts can have a major negative ecological impact. Because it is necessary for the metabolism of insulin, chromium can be hazardous in excessive doses, which can irritate skin and even cause cancer.

10.2.3 Organic Waste

When organic wastes from plants, animals, or artificial sources break down, they put oxygen demands on microorganisms, which lower the dissolved oxygen levels that are vital to aquatic life. The consequent drop in dissolved oxygen has a negative impact on the physiology and metabolism of aquatic species, which eventually causes them to die and the quality of the water to deteriorate.

10.2.4 Endocrine Disruptors (EDCs)

In aquatic populations, exogenous drugs called endogenous hormone substitutes (EDCs) can be detrimental to long-term survival and reproductive success. Pesticides from agricultural runoff, pharmaceutical manufacturing facilities, hospital effluent, and animal and human excrement are some of the sources of EDCs.

10.2.5 Hydrocarbons

The use and disposal of crude oil results in the presence of petroleum hydrocarbons in wastewater, which provide serious health and environmental hazards. Their presence can harm an animal's or human's organs or systems, resulting in a variety of illnesses and ailments.

10.2.6 Bacteria, Viruses, Protozoa, and Pathogens

Significant health hazards can arise from bacteria, viruses, protozoa, and pathogens found in wastewater. These microorganisms can cause a variety of waterborne illnesses that are spread by fecal-oral routes, as well as diseases like malaria, typhoid fever, diarrhea, and amebiasis.

10.3 OTHER POLLUTANTS

The possible health and environmental effects of disinfection by-products (DBPs), microplastics, and nanomaterials discovered in wastewater have sparked concerns. DBPs are created during the disinfection of water, but microplastics—plastic particles smaller than 5 mm—have drawn increasing attention due to their persistence and possible negative effects on the environment.

10.4 USES OF TREATED WASTEWATER

As a non-conventional water supply, treated wastewater effluent from municipal sewage systems is inexpensive, renewable, and visually appealing. Among the many uses for the treated wastewater are as follows:

- Agriculture
- Domestic use (such as toilet flushing).
- Fighting fires.
- Watering of golf courses and parks.
- Using wetlands as habitats for wildlife.
- Impoundments for recreation.
- Industrial use (such as boiler feed water, cooling water makeup, etc.)

The potential for wastewater reuse is based on its qualities, which also dictate the kind and extent of treatment needed. Wastewater that has been treated is useful for non-potable uses. Reusing non-potable water can lower the amount of water used from outside sources and slow the flow rate of waste water.

10.5 EMERGING TRENDS IN WASTEWATER TREATMENT TECHNOLOGIES: BIOLOGICAL TREATMENT TECHNOLOGIES

Strict laws and the possibility of hefty fines for exceeding discharge restrictions have been major forces behind the development of new or improved wastewater treatment technology. Innovative therapeutic approaches have emerged as a result of this financial impact on industries. Because they are economical and environmentally friendly, anaerobic and aerobic technologies have become more and more popular for treating organic wastewater in recent years. In particular, anaerobic methods stand out for using minimal amounts of energy. The removal of nutrients from wastewater is a critical function of biological treatment methods, which provide long-term and reasonably priced ways to reduce nutrient pollution. We seek to clarify these technologies’ benefits, drawbacks, and possible uses in wastewater nutrient removal through a thorough examination (Kamilya et al., 2022, Saravanan et al., 2021, Sathya et al., 2023).

10.5.1 Constructed Wetlands

Constructed wetlands are artificial systems that are made to take use of the natural processes that occur in wetland soil, plants, and microbial communities to help clean wastewater. Water flows into a lined cell that makes up constructed wetlands. The roots of the plants in each cell remove impurities from the water (Figure 10.1).

10.5.2 Rapid Infiltration

Another natural technique is known as fast infiltration, which involves filling a basin with wastewater that has previously undergone pre-treatment. The contaminants are filtered out of the water by the ground. This process is comparable to that of a septic system (Figure 10.2).

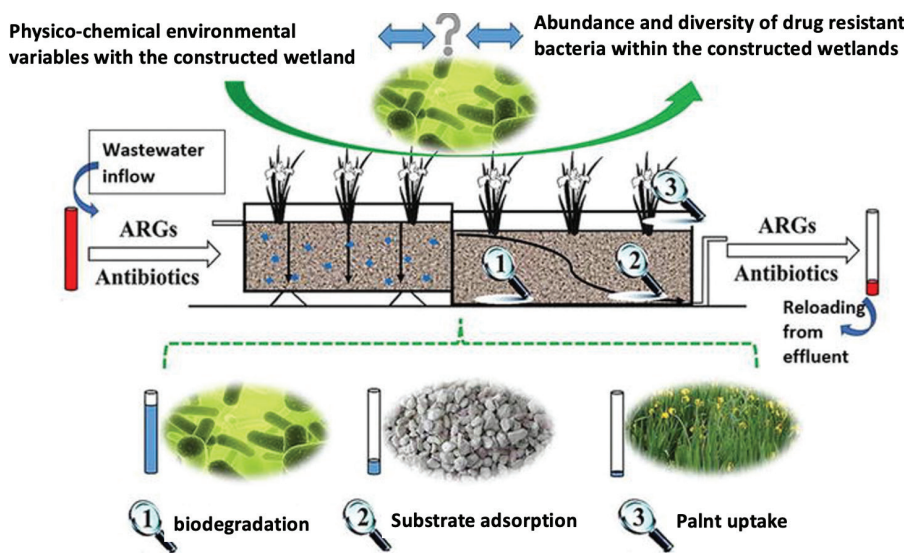


FIGURE 10.1 Constructed wetland. (Source: Gekenidis et al., 2018; Jun et al., 2019.)

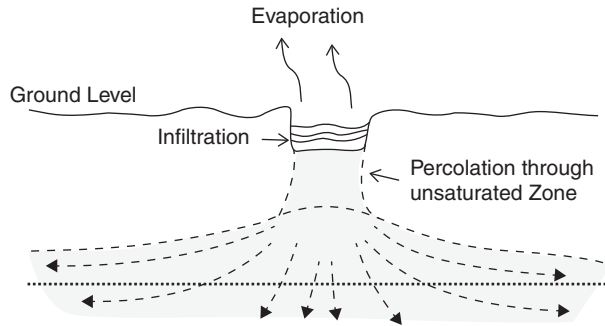


FIGURE 10.2 Rapid filtration treatment. (Source: Mexal et al., 2002.)

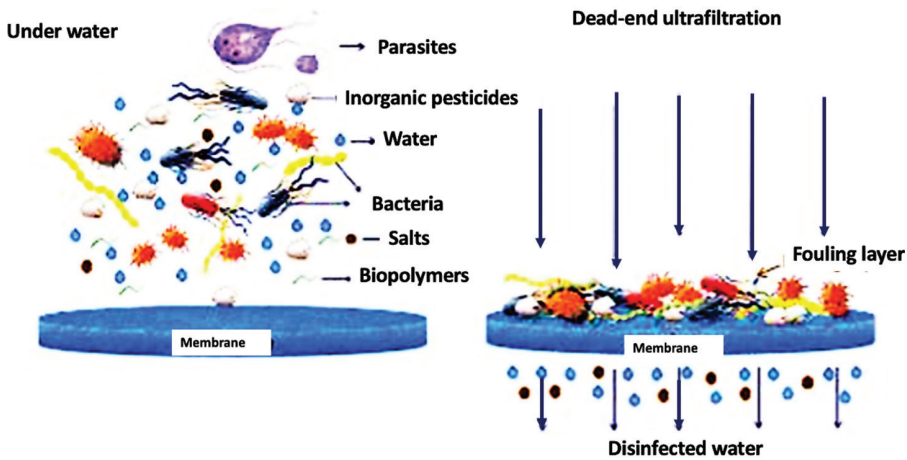


FIGURE 10.3 Membrane Filtration Technique. (Source: <https://www.eawag.ch/en/info/portal/news/news-detail/swiss-water-research-at-the-un-summit-in-new-york/>.)

10.5.3 Membrane Filtration Technologies

A broad definition of membrane filtration is a separation procedure that separates the feed stream into two parts using a semipermeable membrane: an infiltrate, which contains the material going through the membrane, and a retentate, which is made up of the species that are left behind. More precisely, the size range of species that can permeate, the rejection processes, the driving power used, the chemical makeup and structure of the membranes, and the construction geometry can all be used to further categorize membrane filtration. Pressure-driven methods, such as reverse osmosis (RO), microfiltration (MF), ultrafiltration (UF), and nanofiltration (NF), are the most significant forms of membrane filtration (Figure 10.3).

10.5.4 Advanced Oxidation Technology

Advanced oxidation processes, or AOPs, are generally characterized as treatment procedures carried out at or close to ambient temperature using extremely reactive radicals as their main oxidant, particularly the hydroxyl radical (OH). Clearly, one of the most effective oxidizing species employed in the treatment of

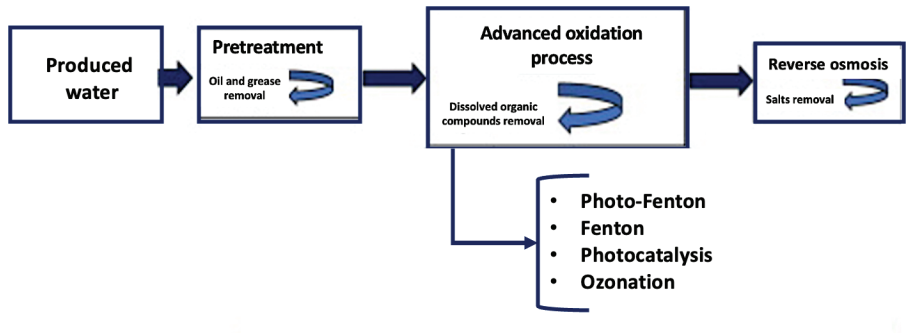


FIGURE 10.4 Advanced oxidation technology. (Source: Jiménez et al. 2019.).

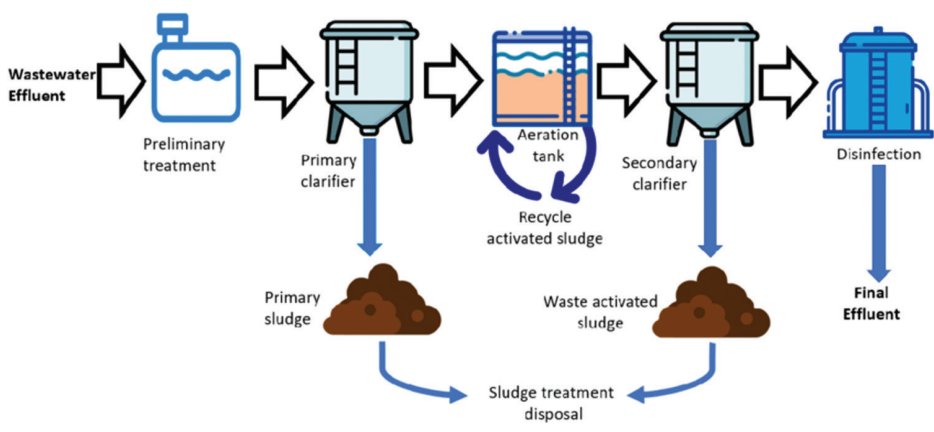


FIGURE 10.5 Activated sludge process. (Source: Ayu, 2023.)

water and wastewater is the OH radical, which has the ability to significantly increase the rates at which contaminants oxidize the current generation. The usual ways to accelerate OH radicals are to combine UV light, ultrasound, heterogeneous photocatalysis, ozone (O₃), hydrogen peroxide (H₂O₂), titanium dioxide (TiO₂), and/or intense electron beam irradiation (Figure 10.4).

10.5.5 Activated Sludge Process

One of the most popular biological treatment techniques for treating wastewater is the activated sludge process, which is well known for its efficiency in eliminating nutrients and organic materials. In this procedure, wastewater is mixed with an activated sludge microbial culture in aeration tanks, where microorganisms break down organic materials and produce biomass from nitrogen and phosphorus. The mixed liquor is then allowed to settle in clarifiers, and the clarified effluent is either released or given additional treatment. High removal efficiency for organic matter and nutrients, operational flexibility, and comparatively inexpensive capital costs are only a few benefits of the activated sludge process. But problems like foaming, sludge thickening, and the requirement for constant upkeep and observation might reduce its effectiveness and dependability in removing nutrients (Figure 10.5).

10.5.6 Sequencing Batch Reactors (SBRs)

Sequencing batch reactors, or SBRs, are becoming more and more well known as effective and adaptable biological wastewater treatment methods. With batch mode operation, SBRs enable the sequential stages of filling, aeration, settling, and decanting all done in one reactor vessel. Through alternating anaerobic, aerobic, and anoxic settings, this cyclic operation allows for excellent control over treatment conditions and supports biological nutrient elimination. Reduced footprint, improved nutrient removal efficiency, and flexibility to adjust to changing influent characteristics are just a few benefits of using SBRs. But to maximize performance, SBRs need complex control systems and monitoring procedures, and problems with bulking, foaming, and filamentous growth can impact treatment dependability (Jagaba et al., 2021, Jena et al., 2020, Lawal et al., 2023) (Figure 10.6).

10.5.7 Membrane Bioreactors (MBRs)

Membrane bioreactors (MBRs) are designed to produce high-quality wastewater that may be discharged or reused by combining membrane filtering technology with biological treatment procedures. In MBRs, biomass concentration and extended solids retention times are made possible by the retention of microorganisms inside the bioreactor through the use of ultrafiltration or microfiltration membranes. This arrangement efficiently removes pathogens and suspended materials while creating a favorable environment for biological processes, which improves the efficiency of nutrient removal. Compared to traditional activated sludge systems, MBRs have benefits such as smaller footprint, better effluent quality, and less sludge production (Al-Asheh et al. 2021; Monteoliva-García et al., 2020; Rahman et al., 2023). Nevertheless, MBRs are prone to membrane fouling, which raises the cost of operation by requiring frequent cleaning and maintenance (Figure 10.7).

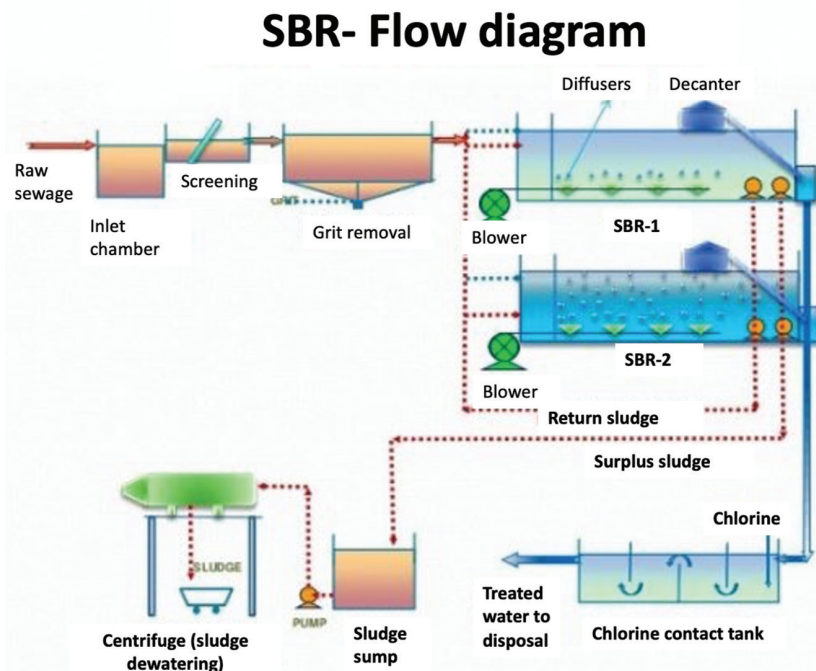


FIGURE 10.6 Sequencing batch reactors (SBRs). (Source: Irvine and Davis, 1971; Irvine and Busch, 1979.)

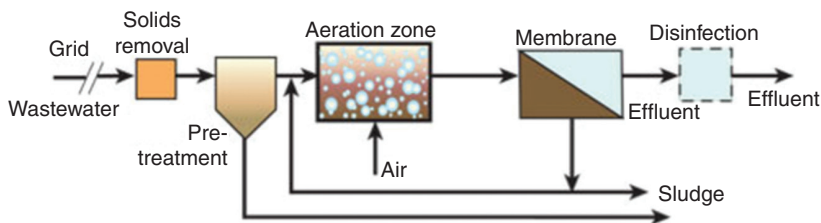


FIGURE 10.7 Membrane bioreactors (MBRs). (Source: Pandey and Singh, 2014.)

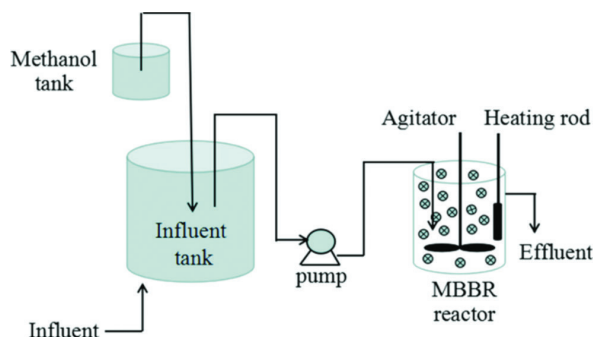


FIGURE 10.8 Moving bed biofilm reactors (MBBRs). (Source: Wang et al., 2020.)

10.5.8 Moving Bed Biofilm Reactors (MBBRs)

The purpose of moving bed biofilm reactors (MBBRs) is to provide a platform for microbial attachment and growth by using suspended biofilm carriers inside aerated tanks. Microorganisms affixed to the biofilm transporters break down organic materials and nutrients as wastewater passes through the reactor, making it easier for the wastewater stream to be cleared of them. High biomass retention, resistance to changes in hydraulic and organic load, and low sludge production are only a few benefits of using MBBRs. Furthermore, MBBRs may effectively remove nitrogen by achieving simultaneous nitrification and denitrification. However, to maximize efficiency and avoid biofilm separation, MBBRs need to have precise control over aeration rates, carrier-to-water ratios, and hydraulic conditions (Figure 10.8).

10.5.9 Integrated Fixed-Film Activated Sludge (IFAS)

To increase the effectiveness of nutrient removal, integrated fixed-film activated sludge (IFAS) systems integrate attached growth and suspended growth processes into a single unit. These systems add biofilm media, such as structured media or plastic carriers, to activated sludge reactors, giving microorganisms a surface to adhere to and create biofilms. Compared to conventional activated sludge procedures, this hybrid setup improves nutrient removal kinetics, lengthens the solids retention duration, and raises biomass concentration. Because of their flexible operation and design, IFAS systems are useful for treating wastewater from both industrial and municipal sources by removing nutrients. But problems including media deterioration, clogging, and biofilm aging can affect system efficiency and call for routine maintenance according to Waqas et al. (2023), Waqas et al. (2020), and Zhao and Bai (2022) (Figure 10.9).

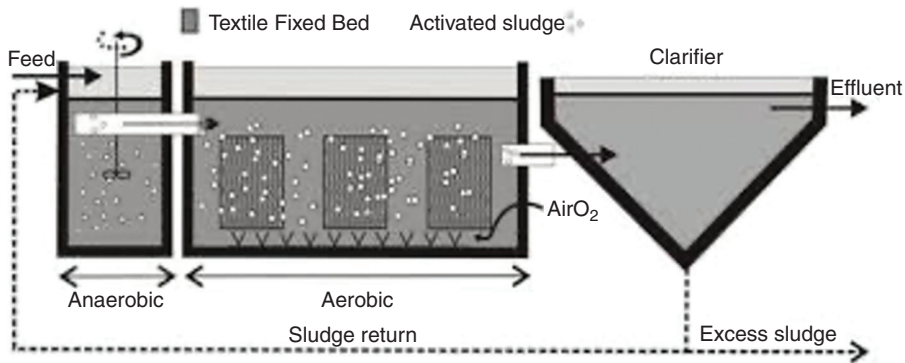


FIGURE 10.9 Integrated fixed-film activated sludge (IFAS). (Source: Malovany et al., 2015.)

10.6 CONCLUSION

Nutrient removal is one of the many advantages of using biological technologies to clean wastewater. They are renowned for their sustainability, operational versatility, and high nutrient removal efficiency. Using natural microbial processes, these techniques reduce the harmful effects of wastewater discharge on the environment by breaking down organic matter and converting nutrients into biomass. These treatment systems are appropriate for a variety of applications because they may be tailored to fit particular treatment objectives and site conditions. It is crucial to remember that biological treatment techniques have disadvantages as well. These disadvantages include the need for careful monitoring and maintenance, susceptibility to operational disturbances, and potential problems including sludge thickening and foaming. It could be necessary to use additional treatment technologies and sophisticated management systems to remove nutrients with consistency. The type of wastewater itself is a major factor in choosing a treatment technology for wastewater. To determine crucial factors like chemical oxygen demand (COD), total solids (TS), volatile solids (VS), and salt content, among others, wastewater streams must be analyzed. Three cutting-edge technologies are highlighted in this section: MFC, microalgal, and membrane technologies. These can be used as part of a treatment plan alone or in combination.

REFERENCES

- Al-Asheh, S., Bagheri, M., & Aidan, A. (2021). Membrane bioreactor for wastewater treatment: A review. *Case Studies in Chemical and Environmental Engineering*, 4, 100109.
- Ayu, R., Seng, B., Kumar, R., & Mohamed, A. (2023). Municipal wastewater treatment technologies in Malaysia: A short review. *Industrial and Domestic Waste Management*, 3(1), 38–46. <https://doi.org/10.53623/idwm.v3i1.243>.
- Faroon, M. A., AlSaad, Z., Albadran, F., & Ahmed, L. (2023). Review on technology-based on reverse osmosis. *Anbar Journal of Engineering Sciences*, 14(1), 89–97.
- Gekenidis, M. T., Qi, W., Hummerjohann, J., Zbinden, R., Walsh, F., & Drissner, D. (2018). Antibiotic-resistant indicator bacteria in irrigation water: High prevalence of extended-spectrum beta-lactamase (ESBL)-producing *Escherichia coli*. *PLoS One*, 13(11), e0207857. <https://doi.org/10.1371/journal.pone.0207857>.
- Irvine, R. L., & Busch, A. W. (1979). Sequencing batch biological reactor: An overview. *Journal of Water Pollution Control Federation*, 51, 235.
- Irvine, R. L., & Davis, W. B. (1971). Use of sequencing batch reactor for wastewater treatment. CPC International, Corpus Christi, TX. Presented at the 26th Annual Industrial Waste Conference, West Lafayette, IN: Purdue University.

- Jagaba, A. H., Kutty, S. R. M., Noor, A., Birniwa, A. H., Affam, A. C., Lawal, I. M.,...&Kilaco, A. U. (2021). A systematic literature review of biocarriers: Central elements for biofilm formation, organic and nutrients removal in sequencing batch biofilm reactor. *Journal of Water Process Engineering*, 42, 102178.
- Jena, J., Narwade, N., Das, T., Dhotre, D., Sarkar, U., &Souche, Y. (2020). Treatment of industrial effluents and assessment of their impact on the structure and function of microbial diversity in a unique Anoxic-Aerobic sequential batch reactor (AnASBR). *Journal of Environmental Management*, 261, 110241.
- Jiménez,S.,Andreozi,M.,Micó,M. M.,Álvarez,M. G.,&Contreras, S. (2019). Produced water treatment by advanced oxidation processes. *Science of the Total Environment*, 666, 12–21. <https://doi.org/10.1016/j.scitotenv.2019.02.128>
- Jun, C.,Deng,W. J., Liu, Y. S.,Hu, L. H.,He, L. Y.,Zhao,J. L., et al. (2019). Fate and removal of antibiotics and antibiotic resistance genes in hybrid constructed wetlands. *Environmental Pollution*, 249, 894–903. <https://doi.org/10.1016/j.envpol.2019.03.111>.
- Kamilya, T., Majumder, A., Yadav, M. K., Ayoob, S., Tripathy, S., &Gupta, A. K. (2022). Nutrient pollution and its remediation using constructed wetlands: Insights into removal and recovery mechanisms, modifications and sustainable aspects. *Journal of Environmental Chemical Engineering*, 10(3), 107444.
- Lawal, I. M., Soja, U. B., Hussaini, A., Saleh, D., Aliyu, M., Noor, A.,...&Jagaba, A. H. (2023). Sequential batch reactors for aerobic and anaerobic dye removal: A mini-review. *Case Studies in Chemical and Environmental Engineering*, 8, 100547.
- Malovany,A.,Trela,J.,&Plaza, E. (2015). Mainstream wastewater treatment in integrated fixed-film activated sludge (IFAS) reactor by partial nitrification/anammox process. *Bioresource Technology*, 198, 478–487.
- Mexal,J. G.,Zachritz,W.,& Sammis,T. W. (2002). Trees are the answer to wastewater treatment for small communities: Case studies. In: National Proceedings: Forest and Conservation Nursery Associations-1 999, 2000, and 2001. Proceedings RMRSP-24, edited by Dumroese, R. K., Riley, L. E., Landis, T. D., technical coordinators. Ogden, UT: USDA Forest Service, Rocky Mountain Research Station, pp. 327–335.
- Monteoliva-García, A., Martín-Pascual, J., Muñoz, M. D. M., &Poyatos, J. M. (2020). Effects of carrier addition on water quality and pharmaceutical removal capacity of a membrane bioreactor–advanced oxidation process combined treatment. *Science of the Total Environment*, 708, 135104.
- Pandey,A.,&Singh, R. (2014). Industrial wastewater treatment by membrane bioreactor system. *Elixir Chemical Engineering*, 70, 23772–23777.
- Rahman, T. U., Roy, H., Islam, M. R., Tahmid, M., Fariha, A., Mazumder, A.,...&Islam, M. S. (2023). The advancement in membrane bioreactor (MBR) technology toward sustainable industrial wastewater management. *Membranes*, 13(2), 181.
- Saravanan, A., Kumar, P. S., Jeevanantham, S., Karishma, S., Tajsabreen, B., Yaashikaa, P. R., &Reshma, B. (2021). Effective water/wastewater treatment methodologies for toxic pollutants removal: Processes and applications towards sustainable development. *Chemosphere*, 280, 130595.
- Sathya, R., Arasu, M. V., Al-Dhabi, N. A., Vijayaraghavan, P., Ilavenil, S., &Rejiniemon, T. S. (2023). Towards sustainable wastewater treatment by biological methods–A challenges and advantages of recent technologies. *Urban Climate*, 47, 101378.
- Su, X., Chiang, P., Pan, S., Chen, G., Tao, Y., Wu, G.,...&Cao, W. (2019). Systematic approach to evaluating environmental and ecological technologies for wastewater treatment. *Chemosphere*, 218, 778–792.
- Wang,T.,Wu, T.,Wang,H.,Dong,W.,Zhao,Y., Chu, Z., Yan, G.,&Chang, Y. (2020). Comparative study of denitrifying-MBBRs with different polyethylene carriers for advanced nitrogen removal of real reverse osmosis concentrate.*International Journal of Environmental Research and Public Health*, 17, 2667. <https://doi.org/10.3390/ijerph17082667>
- Waqas, S., Bilad, M. R., Man, Z., Wibisono, Y., Jaafar, J., Mahlia, T. M. I.,...&Aslam, M. (2020). Recent progress in integrated fixed-film activated sludge process for wastewater treatment: A review. *Journal of Environmental Management*, 268, 110718.
- Waqas, S., Harun, N. Y., Sambudi, N. S., Abioye, K. J., Zeeshan, M. H., Ali, A.,...&Alsaadi, A. S. (2023). Effect of operating parameters on the performance of integrated fixed-film activated sludge for wastewater treatment. *Membranes*, 13(8), 704.
- Zhao, W., &Bai, M. (2022). Upgrading integrated fixed-biofilm activated sludge (IFAS) system into separated two-sludge denitrifying phosphorus removal system: Nutrient removal and microbial structure. *Chemosphere*, 307, 135918.

Microbial Desalination Cells

Trends and Challenges

11

Prem Baboo

ABBREVIATIONS

EDI	Electro deionization
NF	Nano filtration
MED	Multi effect distillation
EDR	Electrolyse reversal
AEM	Anion-exchange membrane
BPM	Bipolar membrane
CEM	Cation-exchange membrane
CE	Coulombic efficiency
DR	Desalination rate
FO	Forward osmosis
IEMs	Ion-exchange membranes
MDC	Microbial desalination cell
MEDC	Microbial electrolysis desalination cell
MEDCC	Microbial electrolysis desalination and chemical-production cell
MFC	Microbial fuel cell

11.1 INTRODUCTION

MDC will prove to be very profitable in future, but further advancements are required. There are many challenges in this process that need to be addressed. Taking technology to large scale presents various technological challenges that must be overcome for commercial and large scale.

Microbial desalination cells process has proven to be one of the useful and environment friendly technologies, capable of treatment of wastewater as well as seawater desalination, and eco-energy production.

Bioelectrochemical systems are emerging, innovative technologies that hold promise-based concepts for energy recovery and wastewater treatment. These systems use microorganisms to convert the chemical energy present in wastewater into electrical energy through various biochemical reactions. The electrical energy is generated with the help of bioelectrochemical oxidation of organic matter in wastewater. The conventional reverse osmosis process for desalinating salt water consumes excessive electrical and mechanical energy. For example, the energy used to purify seawater is approximately 4.0–5.0 kWh/m³. Thermal technologies are also used in seawater desalination, such as multieffect desalination (MED) and multistage flash (MSF). However, they have several disadvantages from a climate change perspective as shown in Figure 11.1. Recently, many global studies have focused on implementing desalination processes powered by renewable energies, such as wind, solar, geothermal, and bioenergy. However, renewable energy-powered desalination processes are more expensive than conventional processes. Therefore, developing a sustainable, inexpensive, and efficient desalination technology is necessary. Microbial desalination cells are a promising bioelectrochemical technology for desalinating seawater, requiring little or no energy (Figure 11.2). The Microbial Fuel Cells are bioelectrochemical devices that use microorganism to

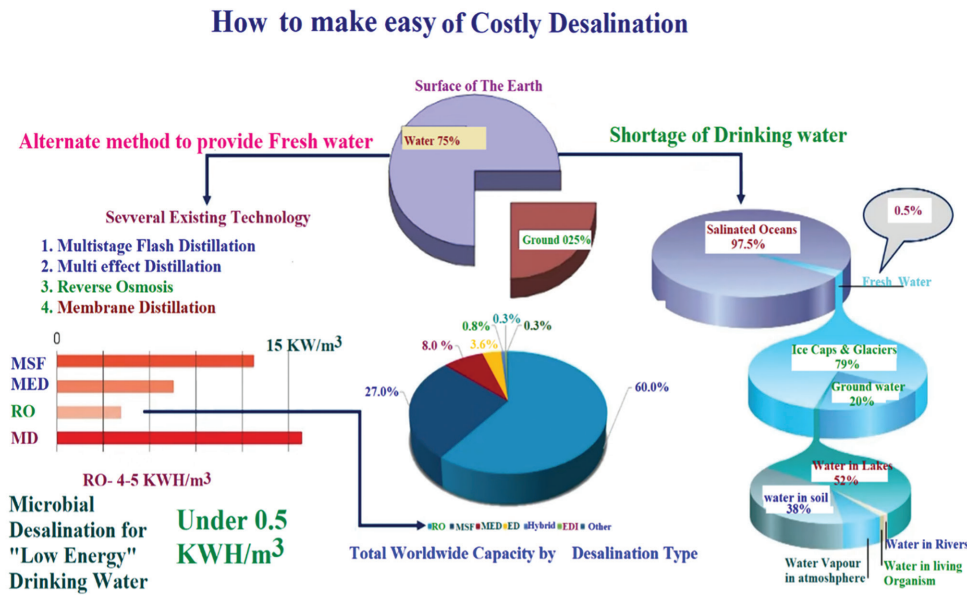


FIGURE 11.1 How to make easy of costly desalination.

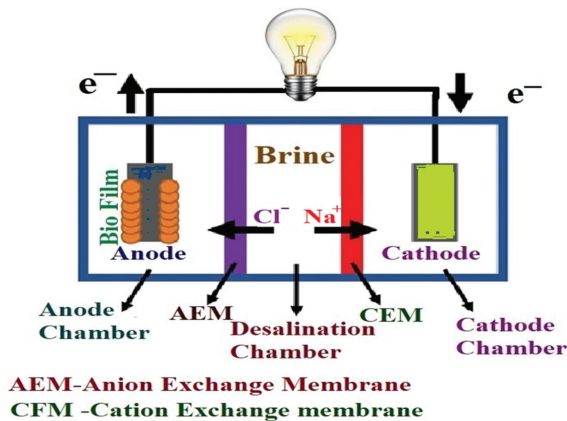


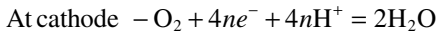
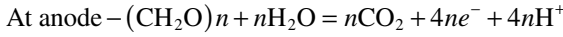
FIGURE 11.2 Microbial desalination cells.

convert organic matter into electrical energy. The sustainability of MDC is attributed to their ability to use wastewater organics as the driving force to desalinate saline or brackish water while simultaneously enabling biological wastewater treatment and power generation.

As per the survey conducted by the International Desalination Association in 2015, approximately 18,426 desalination plants are functioning in 150 countries and provide 86.8 million cubic meters/day.

11.2 WORKING PRINCIPLE

The MDC structure resembles that of a microbial fuel cell. Exchange of ions takes place with the help of membrane. This membrane is of special type and each membrane has distinct specifications that allow the transfer of ions into the chamber. It has anode where organic matter from waste water forms a biofilm and the electron flow takes place, producing an electric current. Cathode is the aerobic chamber that produces potential differences and middle chamber is filled with saline water. At the anode, electricity is produced by the breakdown of organic matter containing in the wastewater. In the middle chamber, salts are removed from the saline water. The biofilm on the anode oxidizes pollutants, releasing electrons and protons, which contribute to the current flow. The following equations show the reactions at the anode and cathode.



The electricity produced with microorganism present on waste water or saline water to convert biochemical into electricity. The use of mathematical models is also available to provide an analytical description that might convert complex systematic phenomena into simple series of mathematical expressions to describe the effect of every component on the overall output. The electrons produced from cell by metabolic process move from the anode to the cathode through an external wiring circuit that links the two electrodes and create an electrical field that separates salts in saline water. At the cathode chamber, oxygen issues the electrons from the external circuit to undergo reduction and produce pure water. This causes a potential gradient across the anode and cathode chambers.

$$\text{OP}_{\text{coc}} = \frac{RT}{F} \ln \left\{ \frac{M_{\text{total}}}{M_{\text{read}}} \right\}$$

$$I_{\text{MDC}} = \frac{V_{\text{oc}} - \text{OP}_{\text{conc}}}{R_{\text{ext}} + R_{\text{int}}}$$

where

OP_{conc} is the over potential concentration (v); R_{int} the internal resistance of MDC and R_{ext} is the external resistance (Ω); and V_{oc} the open circuit voltage (v).

The relationship between the current production and methanogenic growth rate is shown in Figure 11.3.

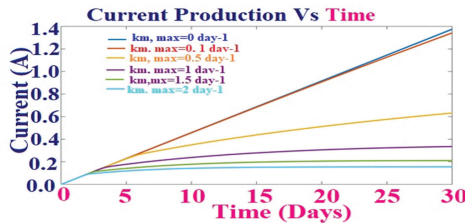


FIGURE 11.3 Current prod vs time. (Source: Khaled et al., 2021.)

The Graph when activated carbon is used in Reactor

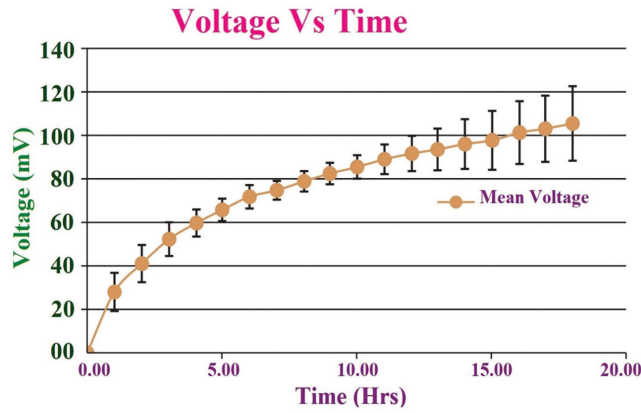


FIGURE 11.4 Voltage vs time with activated carbon. (Source: Aidan et al., 2014.)

To maintain electro neutrality, the anions (Cl^-) flow across the anion-exchange membrane from the salt water in the middle chamber into the anode, while the cations (Na^+) move to the cathode chamber across the cathode exchange membrane (Figure 11.4).

Electron transfer takes place in three ways by bacteria: first the electron is transported to the growing media. Then transfer is done to the anode. A terminal protein bound to the outer surface of the cells from the growing media transfers the electrons directly to the anode. The nature of terminal cells is completely different from each other. The current production vs. time varies for different methanogenic growth rate values (with the influent substrate concentration, $S_{\text{in}} = 1,000 \text{ mg}_\text{s}/\text{L}$). Biofilm is generated in the MDC chamber, which acts as a catalyst that generates more current. The biofilm bacteria are capable of transferring electrons to the anode without the need of an electron acceptor. There is density increased in biofilm. The thickness of the biofilm also produced more current. The biomass is inversely proportional to current production; this is due to the presence of voids in the interior of the biofilm. To produce high current, there is low resistance required in external circuit. Different model and design produced by some of scientist are mentioned as given in Table 11.1.

Till now, different models have been introduced and further research is going on. It is expected that in the future, we will get pollution free electricity and water. This is a game of bacteria in the world.

11.3 BIOFILMS

Biofilm is a layer of bacteria or other microbes that grows on and sticks to the surface of a structure or the bacteria which live in social groups called “biofilms”. Biofilm is bound by a matrix and it depends on many factors like temperature and surrounding environmental conditions particularly humidity. These cells stick together after finding suitable surface conditions and the cells start multiplying by cellular division. This is a very slow process having four stages as shown in Figure 11.5. The biofilm develops in an anodic chamber of a micro desalination cell and acts as a catalyst to promote the bioreaction. The biofilm bacteria, thickness, and age of biofilm are helpful in increasing production. However, biofilm thickness and biomass density are inversely proportional due to the presence of interior voids. Biofilm promoting and inhibiting bacterial biofilm growth and electroactive bacteria present in the biofilm act as catalysts and promote reductive oxidative reactions. After biofilm formation on the cathode, the reaction becomes longer as shown in phase 1. It also has a drawback when there is crossover of oxygen at the cathode toward the anode. It causes loss of electrons, leading to poor power generation.

TABLE 11.1 MDC Designs, their Electrode Materials, and Capacities

<i>MDC DESIGN</i>	<i>ANODE MATERIAL</i>	<i>CATHODE MATERIAL</i>	<i>TOTAL VOLUME ML</i>	<i>CE%</i>	<i>VI DENSITY</i>	<i>P/P DENSITY</i>
Three-chamber MDC	Carbon felt	Carbon felt	57		3mA	
Up-flow tubular MDC	Carbon brush	Carbon clot	2,750		70mA	15.6w/m ³
Osmotic MDC					4.6mA	
Stack structure MEDCC	Graphite brush	Wet-proof carbon cloth	53	95	11 A/m ²	...
Hydraulic couple MDC	Carbon graphite fiber brush	Carbon cloth	224	49	..	860 mW/m ²
Spatially decoupling anode and cathode	Carbon cloth	Carbon cloth	4,048	...	187.3	85W/m ²
Cell pair MDC	Carbon brush	Carbon cloth	≥75	27	≈2.5A/m ²	...
Four-chamber MDC	Carbon brush	Carbon cloth	122.4	37.8	0.89mA	...
Novel two-chamber MDC	Carbon fiber brushes	Carbon cloth	1,540	84	43mA	mW.m ³

Source: F.A. Alseroury (2018).

Vol, volume; Mat, material; CE, coulombic efficiency; I, current; P, power.

Development of Biofilm

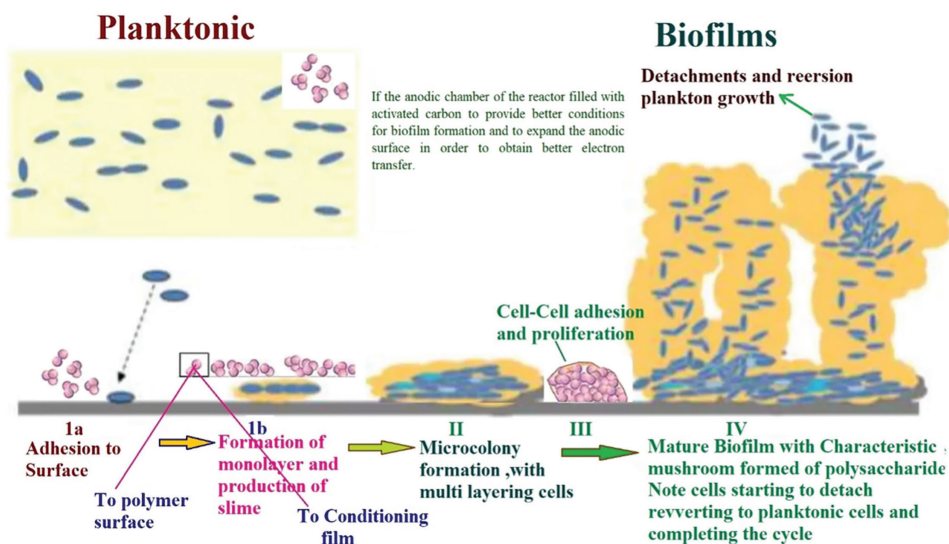


FIGURE 11.5 Development of biofilms.

11.4 MDC SELECTION CRITERIA

There are many factors for selection of MDC, like economic factor and integration with reverse osmosis (RO) and Anaerobic Digestion technology for effective desalination. MDCs are designed to achieve maximum desalination with minimum requirement of energy factors such as material of the electrode, conductivity, ion transfer efficiency, quality of the membrane, substrate and electrolyte pH, and operation conditions.

11.5 MICROBIAL DESALINATION HYBRID SYSTEMS

Till date, the Microbial Desalination Cells (MCD) is not used on a large or commercial scale and remain in the laboratory or experimental stage. Other technology is merged with MCD known as hybrid technology of MCD. The combination of flash distillation, reverse osmosis system and solar system are the combination of MCD system. This hybrid system has high efficiency and comparatively low cost/m³ of water cleaned and power generation is also better. For advancement of the system and better power generation, selection of electrode material is required. Electroactive Bacteria transfer electrons extracellularly via conductive proteins and the biofilm matrix, both of which are influenced by the electrode materials and architecture. Biocompatibility, porosity, and cost, among others, are significant characteristics of electrodes (Figures 11.6 and 11.7; Table 11.2).

11.6 CATHODE MCD OXIDANTS USED

General potassium ferric amide is used as a chemical since it has better efficiency of electron acceptor. However, oxygen is available in atmosphere.

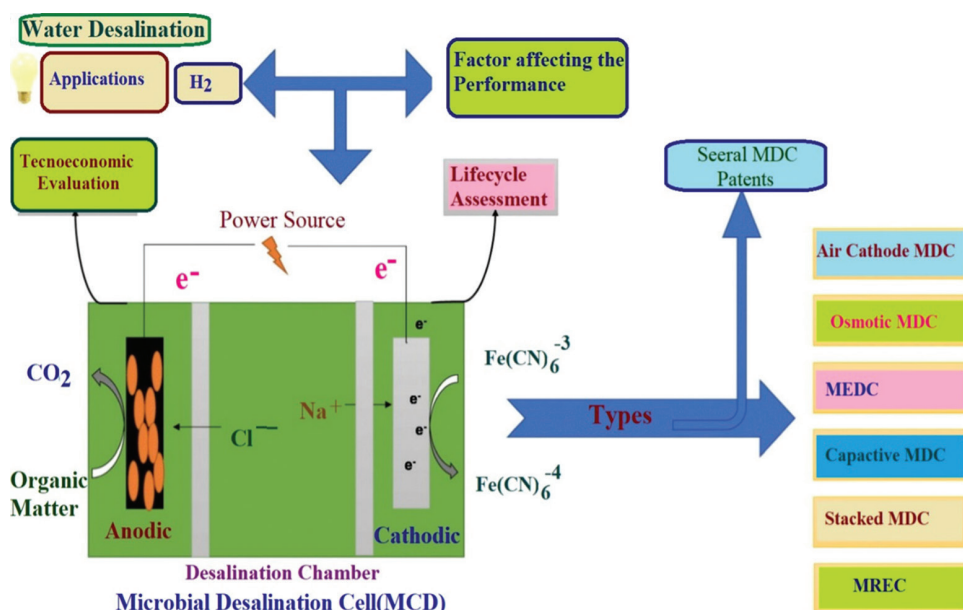


FIGURE 11.6 MCD applications and types of carbon base material such as carbon cloths, felts, and fiber brushes may be used for high efficiency.

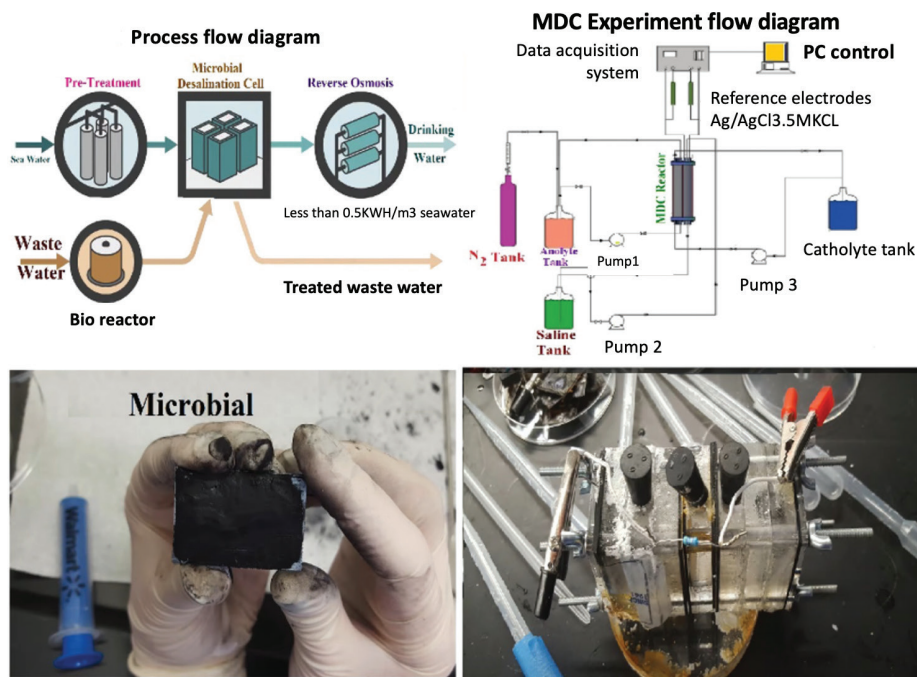


FIGURE 11.7 MCD equipment's.

TABLE 11.2 Types of MDC and their Efficiency Desalination and Current Production Efficiency

<i>MDC TYPE</i>	<i>SALT REMOVAL EFFICIENCY</i>	<i>POWER AND CURRENT POTENTIAL</i>
Photo MDC	Salt concentration was below ca. 1.4 mg/L salt removal efficiency higher than 96%	Power density=8.8 A m ²
Biocatalyst/biocathode in MDC	Higher than 90% of ammonium removal achieved	Current density=0.92W/m ³ Current density=0.814 A/m ³
Sulfonated sodium poly(ether Ether ketone) membrane MDC	Salinity reduction=78.6%	Power generation=235±7 mW /m ²
Ozone-cathode MDC	Salinity reduction=74%	Power density=4.06 W m ²
Photosynthetic MDC	TDS removal=32.2%	Power densities=675 mW/m ³
Silver-tin dioxide (Ag-SnO ₂) composite MDC	Desalination efficiency=72.6%	Maximum power density=1.47 W/m ³
Up-flow MDC	TDS removal rate=7.50 g TDS/L/d	Maximum power density of 30.9W/m ³
Osmosis MDC	Desalination rate=86%	Power density=kWh/m ³
Recirculation MDC	Salinity reduction=39%	The maximum power density was 931±29 mW/m ³
Microalgae MDC	TDS removal>40%	Power density=625 mW/m ³
Quadripartite microbial desalination cell	Desalination rate=72.8%	Max. Power density=8.16 W/m ³
Biocathode microbial desalination cell	Desalination=92%	Maximum voltage=609 mV
Static photosynthetic microbial desalination	Max. TDS removal=32.2%	Power density=753.75 mW/m ²
Anammoxbiocathode		Power density=0.092 W/m ²
Biocathode microbial desalination	Desalination>40%	Power density=of 3.178 W/m ²

11.7 ADVANTAGES OF MICROBIAL DESALINATION CELLS

Our future is seeing a lot of advantages of MCD. While we have achieved a lot on some small scale, it is now the time to take this technology into the commercial sector. MDCs can potentially produce about 1.8 kWh of bioelectricity from the 1 m³ of wastewater. This energy produced by MDC can be used in feedwater pretreatment to lower the salinity to a brackish level, and thus drastically reduce the energy needed for the RO process. The impact of water desalination on the environment has been studied worldwide. The layout of the desalination reactor has been investigated. MDCs can be used to make water potable and to generate some amount of electricity. Following are the key benefits of MCD.

1. Low energy consumption.
2. Waste eater treatments.
3. Fewer chemicals involved.
4. Less waste.
5. High recovery.
6. Positive social impact.
7. A novel technology able to produce sustainable drinking water by using the energy.
8. This technique removes up to 99% of the salts of saline water and produce green energy than what they require.
9. MCDs can also be used in removing heavy metals such as arsenic, nickel, and copper. The activated carbon is used in MDC in both the cathode and anode chambers. The large surface area of the activated carbon provides surface for bacterial growth, thereby leading to the formation of stronger microbial cultures through the formation of biofilms as shown in Figure 11.4.

11.8 DEMERITS OF THE MICROBIAL DESALINATION CELLS

Every coin has two sides. The biochemical reaction is slower compared to an oxidizing substance and a reducing substance (known as redox kinetics) than other catholytes. Cathode's dissolved oxygen concentration requires high energy. Membrane fouling is also the demerits, but today number of membranes discover for bear and tear. Multivalent ions tend to deposit on cation-exchange membrane and biofouling and inorganic deposition occur on anode exchange membrane and also reduces microbial desalination cell efficiency by increasing oxygen concentration in the anode chamber. The environmental risk is also there, and public health impact due to the accidental discharge of active microbial electrolyte solution in the cell has been a thoughtful concern (Table 11.3).

11.9 CONCLUSION

There is no doubt that the microbial desalination cells are an upcoming technology having the potential to minimize power. A lot of experiments are being done in this world regarding MDC on a small scale. The challenge lies in research and development to find out energy requirements and conversion efficiency. Many tests have been done. In principle, MDC could be combined with wastewater and water treatment,

TABLE 11.3 Water Application Value

PROCESS	TDS,MG/LT,RO	PRESSURE, BAR	ENERGY KWH/M ³	ELECTRICITY COST DOLLAR/DAY	MEMBRANE
Without MDC	380000	62.5	6.22	32.8	Sea water
With MDC	8010	12.4	1.23	6.5	Brackish water

Source: F. A. Maqbali(2021).

allowing energy to be recovered from Chemical Oxygen Demand degradation and potentially producing electricity. However, there is still a need for improvement in MCD technology in terms of material and design. MDCs harness the power of bacteria to desalinate water, making them a promising technology for sustainable water supply and environment friendly. Many experiments have been done on a laboratory scale worldwide. Some pilot plants have been evaluated, but no large-scale plant has been established in the world yet. Now we have to see what challenges we face on a large scale, such as the development of membrane cleaning procedures, etc.

REFERENCES

A. Aidan, G. A. Hussein, H. Yemendzhiev, V. Nenov, A. Rasheed, H. Chekkath, Y. Al-Assaf, Microbial desalination cell (MDC) in the presence of activated carbon, advanced science, *Engineering and Medicine*, 6, 2014, 1–5.

Z. Imoroa, M. Mensahb, R. Buamah, Developments in the microbial desalination cell technology: A review, *Water Energy Nexus*,4,2021. doi:10.1016/j.wen.2021.04.002

H. Khaled, Zrelli, A., M. Hamed, B. Chaouachi, Modelisation and optimization of a microbial desalination cell system, *Journal of Sustainable Bioenergy Systems*, 11(3),2021. Laboratory of Energy, Water, Environment and Processes, National Engineering School of Gabes, Gabes, Tunisia. doi:10.4236/jsbs.2021.113009

F. A. Maqbali, *Breaking the Wall of Costly Desalination*, Falling Walls Lab.Berlin,2021.

H. M. Saeed, G. A. Hussein, S. Yousef, J. Saif, S. Al-Asheh, A. Abu Fara, S. Azzam, R. Khawaga, A. Aidan, Microbial desalination cell technology: A review and a case study, *Desalination*, 359, 2015, doi:10.1016/J.desal.2014.12.024

M. Zahid, N. Savla, S. Pandit, V. Kumar Thakur, S. P. Jung, P. Kumar Gupta, R. Prasad, E. Marsili, Microbial desalination cell: Desalination through conserving energy, *Desalination*, 521, 2022, 115381.

Wastewater

Environmental, Social and Health Effects

12

Hind Abdellaoui and Ilias Mouallif

12.1 INTRODUCTION

An increasing demand for water to produce food, supply industries and daily life needs has headed to competition for uncommon freshwater supplies. Wastewater use is progressively seen as an option to meet these growing needs for water [1].

In a general way, wastewater is considered as any altered water in quality by anthropogenic influence, representing a complex mixture of contaminants originating from domestic, industrial, agricultural and urban sources [1]. For instance, the agricultural sector is the largest user of water and wastewater with approximately 70% of water use on average [2]. The wastewater irrigation can contribute to food and water security by providing a reliable year-round source of water with enough nutrients for crop growth [3], especially in regions with critical water stress and increased precipitation variability [4]. The increasing volume and complexity of wastewater have raised concerns about its impacts on environmental sustainability, public health and social equity [5]. To address the challenges associated with wastewater management, a comprehensive understanding of their different sources, compositions and potential impacts on ecosystems and human health is necessary [1].

Wastewater discharge meaningfully affects aquatic ecosystems, leading to water pollution, degradation of water and soil quality and loss of biodiversity in both freshwater and marine environments [6]. The release of pollutants into waterways disrupts ecological balance, threatens sensitive species and compromises the overall health and resilience of aquatic and terrestrial ecosystems [7]. Water pollution resulting from wastewater discharge alters the physical, chemical and biological properties of aquatic environments, compromising water quality and ecosystem functioning [7]. The cumulative impacts of wastewater pollution on freshwater resources and marine ecosystems highlight the urgency of adopting sustainable wastewater management practices to mitigate environmental degradation and preserve ecosystem integrity [7,8]. Additionally, communities affected by water pollution face challenges in accessing clean drinking water and adequate sanitation, increasing risks to public health and food security [1]. Besides, the livelihoods of local populations, particularly in urban and rural areas, are negatively impacted by inadequate wastewater management practices, exacerbating socio-economic disparities and perpetuating cycles of poverty. Access to safe drinking water and sanitation is a fundamental human right,

essential to maintaining health, dignity and socio-economic well-being [9]. However, millions of people around the world lack access to improved water and sanitation services, putting them at increased risk of water-borne diseases, malnutrition and economic hardships. Wastewater pollution compounds these challenges, contaminating water sources, degrading ecosystems and compromising human health and livelihoods. Ultimately, for an effective wastewater management, a holistic approach is required to integrate advanced treatment technologies, public awareness campaigns and robust policy and regulatory frameworks. Implementing sustainable wastewater management practices is essential to mitigate environmental degradation, protect public health and promote socio-economic development [9,10].

In this chapter, we explore wastewater and wastewater management in more detail to address the complex environmental, social and health challenges posed by wastewater. The first part of the chapter will focus on wastewater, its domestic, industrial and storm categories as well as a detail on the different water contaminants and their absorption. The other parts of the chapter will deal with the environmental, social and health effects of wastewater on soil, water and humans. The last part will be dedicated to the different ways of managing wastewater and water sources.

12.2 INTRODUCTION TO WASTEWATER AND CONTAMINANTS

12.2.1 Categories of Wastewater

Wastewater refers to water that has been used in various domestic, industrial, agricultural or commercial processes and has been contaminated with undesirable substances. These waters are generally classified into three main categories: domestic wastewater, industrial wastewater and rainwater wastewater. Effective wastewater management often involves treating it to remove contaminants before releasing it into the environment, which requires wastewater treatment facilities and stormwater management systems. The three categories of wastewater include [1]:

- **Domestic wastewater:** comes from daily household activities. They include kitchen water (sink), bathroom water (shower, sink), laundry room water (washing machine), as well as toilet water (toilet water). Domestic wastewater contains a variety of organic contaminants such as feces, food residues, detergents, as well as household chemicals. They may also contain pathogenic microorganisms such as bacteria, viruses and parasites. Treatment of domestic wastewater is crucial to remove these contaminants and prevent environmental pollution and the spread of disease [1].
- **Industrial wastewater:** originates from manufacturing, production and cleaning processes in industrial facilities. They can contain a wide variety of contaminants, including toxic chemicals, heavy metals, solvents, oils and chemicals used in industrial processes. The characteristics of industrial wastewater depend on the type of industry and manufacturing processes used. These waters can be highly polluting and often require specialized treatment before being released into the environment or directed to municipal wastewater treatment facilities [1].
- **Storm sewage:** is generated by precipitation and runoff on impervious surfaces such as roads, sidewalks, roofs and parking lots. They collect contaminants such as hydrocarbons, heavy metals, pesticides, fertilizers, urban debris and sediments. Storm sewage can contribute to the pollution of surface waters, waterways and aquatic ecosystems. Stormwater management often involves surface water management techniques, such as creating retention ponds, filter marshes and other green infrastructure to reduce the number of contaminants reaching water sources [1].

12.2.2 Contaminants: Types and Methods

Generally speaking, contaminants are unwanted foreign substances present in the environment, food, water, air or other matrices. They can be classified into several categories, including chemical, biological and physical contaminants.

- **Chemical contaminants:** are synthetic or natural substances that can be harmful to human health and the environment. They include a diverse range of compounds, such as heavy metals (lead, mercury, cadmium), organic chemicals (pesticides, herbicides, solvents), hydrocarbons (from the combustion of fossil fuels), as well as toxic substances such as dioxins and furans. These contaminants can be present in the air (air pollution), water (water pollution), soil (soil pollution), food and even in everyday consumer products. Their detection and analysis often require the use of sophisticated techniques such as chromatography, mass spectrometry and various spectroscopic methods [1].
- **Biological contaminants:** are living agents or substances derived from living organisms that can cause harm to human health. They include pathogenic bacteria (like *E. coli*, *Salmonella*), viruses (like norovirus, hepatitis A), parasites (like *Giardia*, *Cryptosporidium*) and molds. These contaminants can be present in drinking water, untreated foods, unwashed agricultural products and even indoor air contaminated with mold. Methods for detecting biological contaminants include microbiological tests such as culture, PCR (polymerase chain reaction) and other antigen-specific immunological techniques [1].
- **Physical contaminants:** are solid foreign particles found in foods, beverages, medications, water and other products. They include substances such as sand, dust, fibers, glass fragments, metal pieces, stones, etc. These contaminants can come from various sources such as the environment, manufacturing processes, packaging materials or processing equipment. They may cause suffocation, choking or internal injury if ingested. Detection of physical contaminants is often done through visual techniques, the use of sieves, magnetometers, metal detectors and other quality control equipment.

Methods for detecting and analyzing contaminants vary depending on their type and presence. They can include sophisticated laboratory techniques such as chromatography, mass spectrometry and microbiological testing, as well as field methods such as visual observation and the use of sensors. Effective management of contaminants generally involves prevention, control and treatment measures to minimize their impact on human health and the environment [1].

The organic contaminants comprised several compounds like polycyclic aromatic hydrocarbons by using petrochemical effluent to irrigate crops, personal care products and pesticides [11,12]. For instance, South Africa focused more on inorganic chemicals like, e.g., Pb, Cd, Cr and Zn, due to the industrial fields generating industrial effluents in the municipal wastewater and water bodies and presenting a risk of exposure to heavy metals owing to the crop's consumption [13,14]. In Southeast Asia, there is a focus on microbiological and chemical contaminants that are considered to have less priority health risks in countries with low income [15]. As for organic contamination, there is little focus on compounds like pharmaceuticals, plasticizers, endocrine disruptors, PAHs, etc., even though they may present risks to human health and environmental integrity.

12.2.3 Absorption of Contaminants

The absorption of contaminants into food represents a significant issue linked to wastewater irrigation as it's the most common exposure route. Accumulated metals in soil, even in small amounts, represent a challenge in fields with long-run wastewater irrigation owing to frequent exposure for consumers.

Generally, the absorption of heavy metals and metalloids is identified by several factors like soil conditions and vegetable type [1]. In a work by Khan et al. [11] realized in Tianjin, China, they mentioned that leafy vegetables ensure high transfer of Cu, Cd and Ni from soil to plants. In another study, a comparison between several vegetables contaminated with heavy metals in the region of Varanasi India, has been investigated where the results illustrated that highest concentrations are in cabbage, leafy vegetables, lady's finger, eggplant and spinach, compared to gourd varieties [11].

The absorption of organic contaminants varies also by vegetable type [16]. In a study, the authors illustrated the effect a load of organic compounds had on plant absorption in comparison with lettuce and collards [16]. The absorption variation levels could be a key information to determine which vegetables should be grown in fields with specific contaminants [17]. Besides the chemical absorption through the roots, the contaminants can be retained on the crop's surface. These studies represent a challenge to understand and compare the risks to assess contamination, including the wet or dry weight of ratios and chemicals of soil to plant tissue. Hamilton et al. have assessed the risk of enteric infection owing to infrequent consumption of highly contaminated vegetables and compared to the estimated risk owing to more frequent consumption of crops with lower contamination level [18].

12.3 ENVIRONMENTAL IMPACTS OF WASTEWATER

12.3.1 Water Pollution: Effects on Aquatic Ecosystems

Water pollution has devastating effects on aquatic ecosystems, endangering the health of living organisms and the stability of aquatic habitats. Chemical contaminants from industrial, domestic and agricultural wastewater can alter water quality, disrupt biogeochemical cycles and harm biodiversity [1]. Pollutants such as heavy metals, pesticides, herbicides, pharmaceuticals and hydrocarbons can accumulate in sediments, water and tissues of aquatic organisms, leading to toxic bioaccumulation and adverse reproductive effects, affecting the development and health of fish, crustaceans and other aquatic species. Additionally, nutrients from agricultural fertilizers and domestic wastewater can cause excessive eutrophication of water bodies, promoting toxic algae blooms and the formation of dead zones where oxygen is depleted. Additionally, water pollution can disrupt natural habitats, such as wetlands, coral reefs and estuaries, reducing the availability of food resources and providing shelter for many aquatic species. In summary, water pollution places significant pressure on aquatic ecosystems, threatening their resilience, functioning and ability to provide essential ecosystem services to humans and biodiversity [1].

Many studies have been carried out to assess the effects of water pollution on aquatic ecosystems in various regions of the world. For example, a meta-analysis published in the journal *Environmental Pollution* in 2019 examined the effects of water pollution on the biodiversity and health of aquatic ecosystems around the world [1]. This analysis found that water pollution had significant negative effects on species diversity, community structure and ecological processes in aquatic ecosystems [19]. Another study, led by researchers at the University of California, Santa Barbara and published in the journal "Science" in 2018, examined the effects of plastic pollution on marine ecosystems. This study showed that plastic pollution had devastating effects on marine wildlife, with millions of seabirds and marine mammals affected each year by ingesting plastic waste or becoming entangled in plastic debris [1,19].

12.3.2 Degradation of Water and Soil Quality

Degradation of water and soil quality is a major environmental problem that results from various human activities and inadequate management practices [20]. According to the World Health Organization (WHO), around 2.2 billion people worldwide do not have access to safely managed sources of drinking

water and around 4.2 billion people do not have access to basic sanitation services [21,22]. As well as the US Environmental Protection Agency (EPA) estimates that nearly 40% of rivers and lakes in the United States of America are not suitable for swimming, fishing or other recreational uses due to pollution. These alarming figures require urgent action to reduce sources of pollution, promote sustainable management practices of natural resources and restore degraded ecosystems [21,22].

- a. **Deterioration of water quality:** could be due to several factors, including industrial, agricultural, urban and domestic pollution. Industrial discharges of toxic chemicals, domestic wastewater containing feces and household chemicals and agricultural runoff containing nutrients and pesticides are all sources of water pollution. These contaminants can accumulate in rivers, lakes, groundwater and oceans, leading to reduced water quality and adverse effects on human health and aquatic ecosystems. The consequences of water quality degradation include reduced biodiversity, contamination of drinking water sources, spread of water-borne diseases and disruption of aquatic ecosystems [19,20].
- b. **Degradation of soil quality:** through unsustainable agricultural practices, deforestation, urbanization and industrial pollution. Excessive use of fertilizers, pesticides and herbicides in agriculture can cause nutrients and chemicals to leach into the soil, thereby polluting groundwater and nearby waterways. Deforestation and urbanization can lead to the loss of topsoil, soil erosion and reduced soil fertility. Additionally, mining and industrial activities can contaminate soil with heavy metals, toxic chemicals and other contaminants, making land unsuitable for agriculture and other uses. Degraded soil quality can lead to reduced agricultural yields, loss of biodiversity, desertification and increased vulnerability to natural disasters such as floods and landslides [19–21].

12.4 WASTEWATER USE IN AGRICULTURE: A GLOBAL HEALTH CHALLENGE

The wastewater is commonly discharged into bodies of water with or without treatment because of a lack of facilities in many countries [23]. Untreated wastewater is employed for urban and peri-urban agriculture comprising around 11% of global irrigated croplands [24]. Untreated wastewater contains a high number of contaminants from agricultural, industrial and municipal sources causing several health risks such as skin irritants, toxic chemicals and excreta-related pathogens for farmers, workers and their families [23]. Generally, exposure to wastewater is linked to bacterial, viral and protozoan diseases like cholera, salmonellosis, giardiasis, hepatitis A and other diarrheal diseases [5]. Particularly, infections like ascariasis are linked to wastewater exposure leading to anemia and impaired cognitive and physical development [1]. Besides, agricultural workers suffer from skin diseases such as rashes and dermatitis due to frequent contact with untreated wastewater. Moreover, wastewater contaminants like polycyclic aromatic hydrocarbons (PAHs), endocrine-disrupting chemicals and personal care products, generate potential health risks [25]. The WHO has developed guidelines illustrating the contaminant levels in wastewater that are less harmful to human health [5]. Therefore, the WHO guidelines give progressive targets for different wastewater categories since the full treatment of wastewater may not be possible [5].

Using wastewater could be a form of climate change adaptation providing a significant source of water in dry or variable conditions [1]. Ultimately, the health challenges of wastewater contaminants exposure need more serious investigation. From the literature, some researchers conducted three categories of empirical studies measuring the health risks of wastewater irrigation and contamination of crops employed for human consumption [119–25]. Among their results, they mentioned that using a nested case-control study of adults engaged in agricultural activities had skin diseases such as fungal and dermatitis infections linked to occupational exposure to untreated wastewater in Hanoi, Vietnam [12]. In another study,

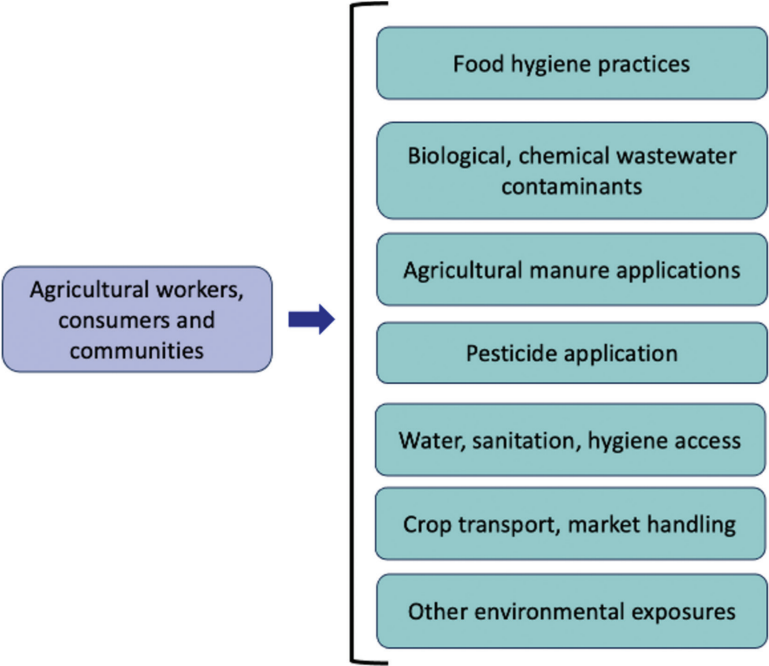


FIGURE 12.1 Wastewater exposure categories.

they reported that in Malamulele, South Africa, the farmers and their families had a higher prevalence of helminth infections (42%) compared with the village (27.5%) [26]. Besides the microbiological risks, some investigations have focused on hair and blood samples to test for heavy metal exposure but without identifying risks from wastewater use [1]. For instance, the study of Cifuentes et al. [27] illustrated no link between agricultural work and Pb blood levels in the Mezquital Valley, Mexico in comparison with other occupations. Also, the farmworkers' exposure is considerable due to the number of possible routes, duration of exposure and frequency. Most research conducted on farmworker exposure investigated microbiological contaminants using epidemiological methods, which were associated with health risks including dermatitis, helminth and diarrheal infections. Moreover, living or commuting near wastewater-irrigated lands may have a risk of indirect exposure, especially children who are more vulnerable to some wastewater contaminants [1]. For instance, cricket games near contaminated soil were identified as a possible source of accidental ingestion [1]. The children can be exposed to wastewater while playing in contaminated fields, which increases the duration and frequency of exposures as well as children are less likely to practice sanitary behaviors such as hand washing [1]. Figure 12.1 illustrates that wastewater exposure is one among several environmental exposures.

12.5 SOCIAL CONSEQUENCES OF WASTEWATER

12.5.1 Access to Drinking Water and Sanitation in Communities Affected by Water Pollution

Access to clean water and sanitation in communities affected by water pollution is a critical issue that affects the health and well-being of millions of people around the world. According to the WHO, approximately 1.8 billion people use a water source contaminated with feces, leading to diarrheal diseases and

other health problems [28]. Additionally, according to the United Nations Children's Fund (UNICEF), approximately 2.2 billion people worldwide do not have access to basic sanitation services. This situation is often exacerbated in areas where water pollution is prevalent, making access to clean, safe water difficult or impossible [29]. Studies such as that carried out by the NGO WaterAid show that in many regions affected by water pollution, women and children are particularly vulnerable. They are often forced to travel long distances to find clean water, which can compromise their safety and deprive them of time for education or other productive activities. Additionally, water pollution can have far-reaching economic effects, with high health costs due to water-borne diseases and productivity losses due to absenteeism from work [30].

Innovative solutions are needed to address this crisis. Projects such as establishing small-scale water purification systems, improving sanitation infrastructure and educating communities on the importance of hygiene can have a significant impact. Additionally, effective government policies and adequate funding are essential to support these initiatives and ensure sustainable access to clean water and quality sanitation services for all communities, even those affected by air pollution [30].

12.5.2 Risks to Food Safety and Public Health

Food safety and public health risks from contaminated water resources are a major concern globally. According to the Food and Agriculture Organization of the United Nations (FAO), around 2 billion people worldwide consume water contaminated with fecal matter, which can lead to the spread of water-borne diseases such as typhoid, cholera and gastroenteritis [31]. This water contamination can also have a direct impact on food security, as it is often used for crop irrigation, livestock watering and food processing [31]. Studies, such as that carried out by the WHO, highlight that water contamination can lead to serious food poisoning [32]. For example, pathogens such as *Salmonella* and *E. coli*, present in contaminated water, can contaminate irrigated crops, making them unsafe for human consumption. Additionally, water pollution can also affect the quality of processed food products, including dairy, seafood and meats, which can lead to large-scale food poisoning outbreaks [32].

To mitigate these risks, water quality management and food safety measures are essential. This includes implementing strict health standards for drinking water and agricultural irrigation, as well as strengthening water and food quality monitoring systems. Additionally, sustainable agricultural practices and efficient water treatment technologies are needed to reduce contamination of water resources and protect public health [31,32].

12.5.3 Impacts on the Livelihoods of Local Populations

Impacts on the livelihoods of local people, caused by factors such as water pollution, climate change and environmental degradation, are of paramount importance. According to the United Nations Environment Program (UNEP), around 1.3 billion people worldwide depend on subsistence agriculture for their survival, and many of these agricultural activities depend directly on access to clean and abundant water resources [33]. Water pollution and reduced availability of water resources can lead to reduced agricultural yields, which can have devastating consequences on the food security and income of rural communities [33]. Studies, such as that conducted by the International Development Research Center (IDRC), highlight the disproportionate effects of these disruptions on the most vulnerable populations, including small-scale farmers, artisanal fishers and resource-dependent populations [34]. For example, water pollution can contaminate water sources used for irrigating crops, leading to reduced yields and loss of income for farmers. Additionally, degradation of aquatic ecosystems can affect the livelihoods of communities that depend on fishing for food and income [34].

To remedy these impacts on the livelihoods of local populations, integrated and sustainable approaches are needed. This includes measures such as establishing resilient agricultural practices, restoring aquatic ecosystems, improving access to clean water and adequate sanitation infrastructure, as well as building

the capacity of communities to face environmental challenges. Inclusive and participatory development policies and programs are also essential to ensure that local people are actively involved in making decisions regarding the management of natural resources that affect their livelihoods [35].

12.5.4 Socio-Economic Problems of Wastewater Management in Urban and Rural Areas

The socio-economic problems associated with wastewater management in urban and rural areas are multiple and have a significant impact on communities. According to the WHO, approximately 80% of the world's wastewater is released into the environment without adequate treatment, leading to water and land pollution [28]. In urban areas, this can lead to water-borne diseases, increasing the burden on health systems and causing additional healthcare costs for individuals and governments [28]. Additionally, water pollution can impact local industries such as tourism and fishing, leading to loss of income for populations dependent on these sectors. In rural areas, inadequate wastewater management can also have serious consequences [28]. Rural populations, often lacking wastewater treatment infrastructure, may be exposed to increased health risks due to contamination of drinking water sources by wastewater. This can lead to an increase in diarrheal and other water-related illnesses, affecting not only the health of individuals but also their ability to work and support themselves economically. Additionally, soil and water pollution can harm agricultural productivity, reducing crop yields and the availability of water resources for irrigation, compromising the food security and livelihoods of rural populations [28].

To address these socio-economic issues, significant investments in wastewater treatment infrastructure are needed, both in urban and rural areas. Innovative approaches such as the reuse of treated wastewater for agricultural irrigation and non-potable water supply can help alleviate pressure on freshwater resources. Additionally, education and awareness programs are essential to inform communities about the risks of inadequate wastewater management and promote safe and sustainable sanitation practices [36].

12.6 MANAGEMENT SOLUTIONS AND STRATEGIES

12.6.1 Integrated Water Resources Management Approaches

Integrated water resources management (IWRM) approaches play a crucial role in reducing water pollution globally. According to the United Nations Educational, Scientific and Cultural Organization (UNESCO), IWRM is a holistic approach that aims to coordinate the management of water resources within the framework of sustainable development [37]. The principles of IWRM include participatory planning, sustainable watershed management, efficient water use and protection of water quality [37]. These approaches have demonstrated effectiveness in reducing water pollution by fostering collaboration among stakeholders, including governments, businesses, local communities and civil society organizations [37]. Studies such as that conducted by the Organization for Economic Co-operation and Development (OECD) highlight the importance of integrated policy instruments to successfully implement IWRM [38]. This may include adopting strong legal and regulatory frameworks, establishing innovative financing mechanisms and strengthening institutional capacities to monitor and evaluate progress. For example, the OECD estimates that effective policy reforms could reduce water pollution in OECD countries by almost 10% by 2050 [38].

Pilot projects for IWRM have been successfully implemented in various regions of the world. For example, the Water Funds project in Latin America, supported by organizations such as The Nature Conservancy, aims to preserve water sources by paying landowners for conservation practices. Similarly, watershed rehabilitation initiatives, such as that led by the United Nations Development Program (UNDP) in Africa, aim to restore natural ecosystems to improve water quality and reduce pollution [38]. To maximize the effectiveness of IWRM in reducing water pollution, an inclusive and adaptive approach is necessary, taking into account local specificities and stakeholder needs [38]. This requires continued commitment from governments, private sector actors and civil society to promote sustainable water management practices and protect water resources for future generations [39].

12.6.2 Good Practices in Sanitation and Waste Management

Raising awareness and educating populations on good practices in sanitation and waste management is essential to improve public health, protect the environment and promote sustainable development. According to the WHO, approximately 2.2 billion people worldwide lack access to basic sanitation services, leading to contamination of water and soil by feces, increasing the risk of diarrheal and other water-borne diseases [28]. Additionally, according to the UNEP, poor solid waste management has become a global problem, with an estimated 2 billion tons of waste produced each year, much of which is dumped in landfills uncontrolled or incinerated without precaution, contributing to air, water and soil pollution [40].

To address these issues, awareness and education programs are essential. Studies such as that conducted by UNICEF show that educating people about the importance of personal hygiene, waste management and using adequate toilets can significantly reduce the spread of related diseases in the water. For example, the Community-Led Total Sanitation (CLTS) initiative, supported by organizations such as WaterAid, aims to mobilize communities to become aware of the dangers of open defecation and adopt practices of safe sanitation [28,38–40]. Likewise, awareness campaigns on waste reduction, sorting and recycling are essential to encourage responsible waste management behavior. Innovative approaches, such as the use of social media and information and communication technologies (ICT), can be effective in reaching a wide audience and promoting behavior change [39]. Research studies, such as those conducted by Harvard University, show that using targeted messages and visual supports can enhance the impact of awareness campaigns on sanitation and waste management practices. In addition, the integration of environmental and sustainable development education into school curricula can help raise awareness among younger generations of issues related to sanitation and waste management, encouraging them to adopt responsible behaviors from an early age [40].

To maximize the effectiveness of awareness-raising and education initiatives, a participatory and inclusive approach is essential, involving governments, civil society organizations, the private sector and local communities. This also requires adequate investments in sanitation and waste management infrastructure, as well as training and capacity building of the actors involved [40].

12.6.3 Policy and Regulatory Frameworks for Sustainable Wastewater Management

Policy and regulatory frameworks play a crucial role in promoting sustainable wastewater management. According to the OECD, effective policies are essential to reduce water pollution and protect freshwater resources. These frameworks provide guidance and incentives to encourage the adoption of good wastewater management practices, including the collection, treatment and reuse of wastewater [38]. An OECD study estimates that the lack of adequate regulations on wastewater management could lead to

an increase in water pollution by 20% by 2050, highlighting the crucial importance of effective policies in this domain. Examples of effective policies and regulations can be found in various countries around the world [38]. For example, the European Union (EU) adopted the Water Framework Directive (WFD), which aims to ensure sustainable management of water resources and prevent water pollution from wastewater. This directive establishes water quality standards and environmental objectives to be achieved, and it also requires Member States to develop watershed management plans to ensure rational and balanced use of water resources. Similarly, countries such as Japan and Singapore have implemented strict regulations on the reuse of treated wastewater for non-potable uses such as irrigation, industry and recreation [38,41].

For these policies and regulations to be effective, it is essential that they are implemented transparently and consistently, with rigorous monitoring and enforcement. Additionally, adequate financing mechanisms must be put in place to support investments in wastewater treatment infrastructure and the search for innovative solutions. Finally, ongoing awareness-raising and education are necessary to inform stakeholders about the challenges of sustainable wastewater management and promote the adoption of good practices at all levels of society [41].

12.7 CONCLUSION

The environmental, social and health impacts of wastewater need to be well understood by the scientific and industrial communities to suggest sustainable solutions. By implementing advanced treatment technologies, effective policies and awareness programs, natural resources can be protected and public health can be enhanced to promote social well-being. In this aim, this chapter dealt with the different effects of wastewater on environmental, social and health aspects, especially for soil, food and human beings. The first part of the chapter focused on the wastewater, its categories and the contaminants and their absorption ways. The core of the chapter was dedicated to the investigation of the different consequences of wastewater on environmental, social and health aspects. In the end, the strategies, policies and regulation ways of water management were detailed.

REFERENCES

1. Dickin SK, Schuster-Wallace CJ, Qadir M, Pizzacalla, K, 2016. A review of health risks and pathways for exposure to wastewater use in agriculture. *Environmental Health Perspectives*, 124. doi:10.1289/ehp.1509995
2. Winpenny J, Heinz I, Koo-Oshima S, Salgot M, Collado J, Hernandex F, et al. 2010. *The Wealth of Waste: The Economics of Wastewater Use in Agriculture*. Rome, Italy: Food and Agriculture Organization of the United Nations. FAO Water Reports 35.
3. Drechsel P, Scott CA, Raschid-Sally L, Redwood M, Bahri A, eds., 2010. *Wastewater Irrigation and Health: Assessing and Mitigating Risk in Low-Income Countries*. London, UK: Earthscan.
4. Hanjra MA, Blackwell J, Carr G, Zhang F, Jackson TM, 2012. Wastewater irrigation and environmental health: Implications for water governance and public policy. *International Journal of Hygiene and Environmental Health*, 215(3), 255–269.
5. WHO, 2006. *Guidelines for the Safe Use of Wastewater, Excreta and Greywater: Wastewater Use in Agriculture*, Volume 2.
6. United Nations Environment Program, 2020. *World Water Quality: Global Wastewater Status Report*.
7. European Environment Agency, 2021. *Water Pollution and Agriculture*.
8. Food and Agriculture Organization of the United Nations, 2020. *Wastewater Reuse in Agriculture: A Literature Review*.
9. American Public Health Association, 2021. *Control of Communicable Diseases Manual*.

10. United Nations, 2018. *The State of Food Security and Nutrition in the World*.
11. Khan S, Cao Q, Zheng YM, Huang YZ, Zhu YG. 2008. Health risks of heavy metals in contaminated soils and food crops irrigated with wastewater in Beijing, China. *Environmental Pollution*, 152, 686–692.
12. Trang DT, van der Hoek W, Cam PD, Vinh KT, Hoa NV, Dalsgaard A. 2006. Low risk for helminth infection in wastewater-fed rice cultivation in Vietnam. *Journal of Water Health*, 4(3), 321–331.
13. Gupta N, Khan DK, Santra SC. 2012. Heavy metal accumulation in vegetables grown in a long-term wastewater-irrigated agricultural land of tropical India. *Environmental Monitoring and Assessment*, 184(11), 6673–6682.
14. Jan FA, Ishaq M, Khan S, Ihsanullah I, Ahmad I, Shakirullah M. 2010. A comparative study of human health risks via consumption of food crops grown on wastewater irrigated soil (Peshawar) and relatively clean water irrigated soil (lower Dir). *Journal of Hazard Mater*, 179, 612–621.
15. Bos R, Carr R, Keraita B. 2010. Assessing and mitigating wastewater-related health risks in low-income countries: an introduction. In: *Wastewater Irrigation and Health: Assessing and Mitigating Risk in Low-Income Countries*. Drechsel P, Scott CA, Raschid-Sally L, Redwood M, Bahri A (eds). London, UK: Earthscan, pp. 29–47.
16. Calderón-Preciado D, Matamoros V, Savé R, Muñoz P, Biel C, Bayona JM. 2013. Uptake of microcontaminants by crops irrigated with reclaimed water and groundwater under real field greenhouse conditions. *Environmental Science and Pollution Research*, 20(6), 3629–3638.
17. Simmons R, Qadir M, Drechsel P. 2010. Farm-based measures for reducing human and environmental health risks from chemical constituents in wastewater. In: *Wastewater Irrigation and Health: Assessing and Mitigating Risk in Low-Income Countries*. Drechsel P, Scott CA, Raschid-Sally L, Redwood M, Bahri A (eds). London, UK: Earthscan, pp. 209–238.
18. Hamilton AJ, Stagnitti F, Premier R, Boland AM, Hale G. 2006. Quantitative microbial risk assessment models for consumption of raw vegetables irrigated with reclaimed water. *Applied and Environmental Microbiology*, 72(5), 3284–3290.
19. Gleick PH et al., 2002. *The World's Water 2002–2003: The Biennial Report on Freshwater Resources*. Washington, DC: Island Press.
20. Carpenter SR et al., 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications*, 8(3), 559–568.
21. Millennium Ecosystem Assessment, 2005. *Ecosystems and Human Well-being: Synthesis*. Island Press.
22. United Nations Environment Programme (UNEP), 2016. *Frontiers 2016 Report: Emerging Issues of Environmental Concern*.
23. Qadir M, Wichelns D, Raschid-Sally L, McCornick PG, Drechsel P, Bahri A et al. 2010. The challenges of wastewater irrigation in developing countries. *Agricultural Water Management*, 97, 561–568.
24. Thebo AL, Drechsel P, Lambin EF, 2014. Global assessment of urban and peri-urban agriculture: Irrigated and rainfed croplands. *Environmental Research Letters*, 9(11), 114002. doi:10.1088/1748-9326/9/11/114002.
25. Dodgen LK, Li J, Parker D, Gan JJ, 2013. Uptake and accumulation of four PPCP/EDCs in two leafy vegetables. *Environmental Pollution*, 182, 150–156.
26. Gumbo JR, Malaka EM, Odiyo JO, Nare L, 2010. The health implications of wastewater reuse in vegetable irrigation: a case study from Malamulele. *International Journal of Environmental Health Research*, 20(3), 201–211.
27. Cifuentes E, Villanueva J, Sanin LH, 2000b. Predictors of blood lead levels in agricultural villages practicing wastewater irrigation in Central Mexico. *International Journal of Occupational and Environmental Health*, 6(3), 177–1820.
28. World Health Organization (WHO), 2020. *Water, Sanitation, Hygiene and Health*. <https://www.who.int/en/news-room/fact-sheets/detail/drinking-water>
29. United Nations Children's Fund (UNICEF), 2021. *Water, Sanitation and Hygiene*. <https://www.unicef.org/fr/wash>
30. WaterAid, 2019. *Global Report on Drinking Water, Sanitation and Hygiene*. <https://www.wateraid.org/fr/where-we-work/global/water-sanitation-and-hygiene-data>
31. Food and Agriculture Organization of the United Nations (FAO), 2020. *Water and Agriculture*.
32. World Health Organization (WHO), 2021. *Water, Sanitation, Hygiene and Health*. <https://www.who.int/en/news-room/fact-sheets/detail/drinking-water>
33. United Nations Environment Program (UNEP), 2020. *Global Environmental Outlook*.
34. International Development Research Center (IDRC), 2019. *Adaptation to Climate Change in Africa*. <https://www.idrc.ca/fr/research-in-action/adaptation-aux-changements-climatiques-en-afrique>
35. Food and Agriculture Organization of the United Nations (FAO), 2021. *Agriculture and Water Resources*.
36. World Bank, 2021. *Wastewater: The Challenge of Managing Water Waste in Cities*. <https://www.banquemondiale.org/fr/topic/wastemangement/brief/wastewater-management-the-challenge-of-managing-water-waste-in-cities>

37. United Nations Educational, Scientific and Cultural Organization (UNESCO), 2021. *Integrated Water Resources Management*.
38. Organization for Economic Co-operation and Development (OECD), 2020. *Reduce Water Pollution*. <https://www.oecd.org/fr/eau/r%C3%A9duit-la-pollution-de-leau-9789264321649-fr.htm>
39. United Nations Development Program (UNDP), 2021. *Watershed Restoration for Increased Water Security in Africa*. <https://www.undp.org/en/content/restoration-watersheds-increased-water-security-africa>
40. United Nations Environment Program (UNEP), 2021. *Pollution Due to Solid Waste*.
41. National Environment Agency Singapore, 2021. *Guidelines for the Reuse of Treated Wastewater*.

Hydrology and Water Resources

13

Challenges of Climate Change Impact

Muthukrishnan MayaKrishnan,
Thirumarai Selvi Chandraraju,
Sadhasivan Gokila, and Mahalingam Jeyakumar

13.1 INTRODUCTION

Hydrology is the scientific study of water on Earth and other planets, focusing on its distribution and management. This field encompasses environmental watershed sustainability, water resources, and the water cycle [1]. Hydrology deals with the properties of water in the atmosphere and on the Earth's surface, including precipitation, evaporation, transpiration, infiltration, groundwater flow, and surface runoff. Surface water hydrology focuses on the study of water in rivers, lakes, and reservoirs, with a detailed analysis of stream flow, river discharge, and the impact of land use on surface water systems. This field is crucial for understanding how water bodies respond to both natural and anthropogenic changes, influencing flood risks and water availability [2]. Groundwater hydrology, or hydrogeology, examines subsurface water in aquifers, including groundwater flow; recharge processes, contamination risks, and sustainable extraction methods. This study is essential for maintaining long-term groundwater supplies, which are vital for drinking water, irrigation, and industrial use [3]. Hydrometeorology investigates the interaction between atmospheric processes and water bodies, focusing on precipitation patterns, the hydrological impact of climate change, and weather-related water phenomena, which are increasingly important in the context of global climate change [4]. Hydro informatics utilizes computational tools and models to address water-related issues, integrating data analysis, modeling, and simulation to enhance water resource management and decision-making [5]. Finally, ecohydrology explores the interplay between hydrological processes and ecosystems, highlighting the importance of water availability for biodiversity, vegetation, and ecosystem services. This approach promotes the use of ecosystem-based management strategies to achieve sustainable water resource management [6].

Water resources refer to the sources of water that are useful or potentially useful to humans. They include rivers, lakes, groundwater, and reservoirs. The management of water resources involves the development, distribution, and sustainable management of water to meet various needs, such as drinking, agriculture, industry, and recreation. Water resources encompass several fundamental ideas that are critical to understanding and managing this vital resource. One of the key principles is integrated water resources management (IWRM), which emphasizes the importance of coordinated development and management across sectors to achieve sustainability, efficiency, and equity in water use [7]. An important concept to consider is water scarcity, which describes the gap between the demand for water and its availability. This idea highlights the escalating challenges that regions worldwide are encountering due to rising populations, climate change, and poor management of water resources, leading to competition for the limited water supplies [8]. Water quality is also an important consideration, focusing on the chemical, physical, and biological properties of water that affect its usefulness for diverse applications such as drinking, agriculture, and industrial. Ensuring good water quality is essential for public health, environmental protection, and economic activities [9]. Ecosystem services provided by water bodies are another critical concept, recognizing the benefits that ecosystems offer, including water purification, flood regulation, and habitat provision. Maintaining healthy water-related ecosystems is vital for sustaining these services and ensuring long-term water availability [10]. Finally, climate change adaptation in water resources management has gained prominence, emphasizing the need for flexible and resilient strategies to cope with the uncertain impacts of climate change on water availability, distribution, and quality [11].

13.2 KEY TERMS IN WATER RESOURCES

Understanding water resources involves several fundamental concepts that are essential for managing and utilizing this vital resource sustainably. Some of the key terms used in water resources are

- i. **Water supply:** Water supply refers to the provision of water by public utilities, commercial organizations, or community projects to meet various human needs. It includes the infrastructure and processes involved in collecting, treating, storing, and distributing water. Molden et al. [12] discuss the critical role of water management in ensuring food security and sustainable agricultural practices.
- ii. **Water quality:** Water quality refers to the chemical, physical, and biological characteristics of water, usually assessed based on its appropriateness for specific purposes, such as drinking, recreational activities, or supporting aquatic ecosystems. Schwarzenbach et al. [13] explore how chemical and biological processes influence the fate of contaminants in various water bodies. WHO [14] provides comprehensive guidelines for maintaining safe drinking water quality, addressing health risks associated with contaminants. Several crucial aspects that define water quality are (a) **pH levels** measure how acidic or alkaline the water is, influencing chemical and biological processes. (b) **Dissolved oxygen** is crucial for the survival of fish and other aquatic organisms, reflecting the water's ability to support life. (c) **Nutrient concentrations** indicate the levels of nitrogen and phosphorus in the water; when these nutrients are present in excess, they can lead to problems like algal blooms, which can degrade water quality. (d) Additionally, **turbidity** refers to the clarity of the water, with higher turbidity potentially affecting aquatic ecosystems and posing risks to human health. These factors are interrelated and collectively determine the overall quality of water.
- iii. **Water demand:** Water demand refers to the overall quantity of water needed by various sectors, including agriculture, industry, and households. It is influenced by factors such as population growth, economic development, and climate conditions. Understanding water demand helps in planning and managing water resources to meet current and future needs. Vörösmarty et al. [9] examine major global threats to water security and river ecosystems, emphasizing the need for integrated management approaches.

- iv. **Surface water:** Surface water is water that collects on the surface of the Earth in rivers, lakes, reservoirs, streams, and oceans. It is a major source of water for human use, including drinking, irrigation, and industrial processes. Management of surface water involves ensuring its availability, quality, and sustainable use. Pahl-Wostl et al. [15,16] study how stakeholder engagement helps to improve water resource management.
- v. **Groundwater:** Groundwater is the water found underground in aquifers, which are layers of rock, sand, or gravel that can hold and transmit water. Groundwater is accessed through wells and springs and is a critical resource for drinking water, agriculture, and industry. Key aspects of groundwater management include recharge rates, sustainable withdrawal, and preventing contamination. Gleeson et al. [17] analyze the water footprint of global food production and its implications for water use efficiency and sustainability.
- vi. **Watershed:** A watershed, also known as a drainage basin, is an area of land that directs all streams and rainfall to a single outlet, such as a river, bay, or other body of water. Watershed management comprises conserving and improving the quality and availability of water within a watershed to ensure its long-term use by all downstream users. Duda et al. [18] highlight the importance of watershed management practices in preserving and improving water quality.
- vii. **Hydrologic cycle:** The hydrologic cycle, commonly referred to as the water cycle, is the ongoing movement of water across, above, and beneath the surface of the Earth. Wagener et al. [19] review various hydrological models and their applications in predicting water availability and management strategies. The hydrologic cycle encompasses several key processes. Precipitation refers to water falling to the Earth in the form of rain, snow, sleet, or hail. Evaporation is the process where water turns into vapor from surfaces such as oceans, lakes, and rivers. Transpiration involves water being released from plants into the atmosphere. Infiltration occurs when water soaks into the ground, replenishing aquifers. Finally, runoff is the movement of water flowing over the surface to rivers, lakes, and oceans. These processes are interconnected and essential for the continuous movement and distribution of water on Earth.

Water resources play a vital role in supporting ecosystems, agriculture, industry, and human livelihoods. They are essential for maintaining healthy ecosystems by providing necessary habitats and sustaining biodiversity [20]. In agriculture, water is crucial for irrigation, enabling the growth of crops and ensuring food security [21]. For industry, water is a fundamental component in various processes, including manufacturing and cooling, driving economic activity [22,23] (Gleick, 2003). Additionally, water resources are indispensable for human livelihoods, as they supply drinking water, sanitation, and recreational opportunities, thereby contributing to overall well-being and quality of life [14].

13.3 CLIMATE CHANGE – INTRODUCTION

Climate change refers to changes in temperature, precipitation, and other atmospheric parameters over long periods. It is primarily caused by the increase in greenhouse gases (GHGs) in the atmosphere which cause warming of the world. The gases in this case include carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) [24]. Many are the activities that cause these gases and they include the industrial activity, deforestation, and burning of fossil fuels.

The relationship between climate change and water resources is multifaceted and significant. Climate change leads to altered precipitation patterns, which can cause more frequent and intense floods or prolonged droughts, affecting water availability and management. Increased global temperatures result in higher evaporation rates from surface water bodies, soil, and vegetation, reducing water levels in rivers, lakes, and reservoirs [25]. The melting of glaciers and ice caps contributes to rising sea levels and impacts freshwater availability, particularly for regions dependent on glacial meltwater [26]. Changes in snowmelt

timing also disrupt water supply systems that rely on seasonal snowmelt, impacting water availability during crucial periods [27]. Additionally, warmer temperatures can increase water temperatures in rivers and lakes, affecting aquatic ecosystems and water quality by decreasing dissolved oxygen levels and promoting algal blooms [28]. These interconnected effects highlight the need for integrated water resource management strategies to address the challenges posed by climate change.

The objective of this chapter is to provide a comprehensive understanding of climate change, its primary drivers, and the subsequent effects on water resources. By examining the interplay between greenhouse gas emissions, global warming, and changes in water patterns, this chapter aims to highlight the implications for water management and the strategies needed to adapt to and mitigate these impacts.

13.3.1 Climate Change Effects on Hydrological Processes

13.3.1.1 Precipitation patterns

Climate change significantly alters precipitation patterns, leading to changes in the intensity, frequency, and distribution of rainfall. These alterations impact groundwater recharge, river flows, and overall water availability. For example, increased rainfall intensity can result in more frequent and severe flooding, while reduced precipitation in some areas can lead to diminished groundwater recharge and lower river flows, affecting water supplies.

Table 13.1 summarizes the changes in annual precipitation by region over the period from 1950 to 2020, highlighting regional variations in rainfall patterns and trends over time. Increased precipitation in some areas and decreased in others highlight the variability and impact of climate change on water resources.

Changes in precipitation patterns due to climate change have significant impacts on water resources. Variations in the intensity, frequency, and distribution of precipitation can lead to alterations in groundwater recharge, affecting the replenishment of aquifers. These changes also influence river flows, potentially causing more frequent and severe floods or prolonged droughts, which, in turn, affect water availability for agricultural, industrial, and domestic use. The shift in precipitation patterns can strain existing water management systems, necessitating adaptive strategies to ensure sustainable water supply amidst these changing conditions.

According to a study by Taylor et al. [29], 10% more precipitation in semi-arid areas can result in a 20%–40% increase in groundwater recharge, whereas 10% less precipitation can result in a 50% decrease in recharge. Similarly, due to decreased precipitation and increasing evaporation rates, river flows in certain locations may decline by up to 25% by 2050, according to the Intergovernmental Panel on Climate Change (IPCC). On the other hand, areas that see more frequent and strong rainfall events might witness a 10%–20% rise in peak river flows, which would increase the likelihood of floods. Additionally, a study by Milly et al. [25] predicted that by 2050, climate changes could lower renewable water resources in some mid-latitude regions by up to 30%.

TABLE 13.1 Changes in Annual Precipitation by Region (1950–2020)
[24,26]

REGION	AVERAGE ANNUAL PRECIPITATION (MM)	CHANGE (%)
North America	900	+5
Europe	800	+2
Africa	400	–10
Asia	1,200	+3

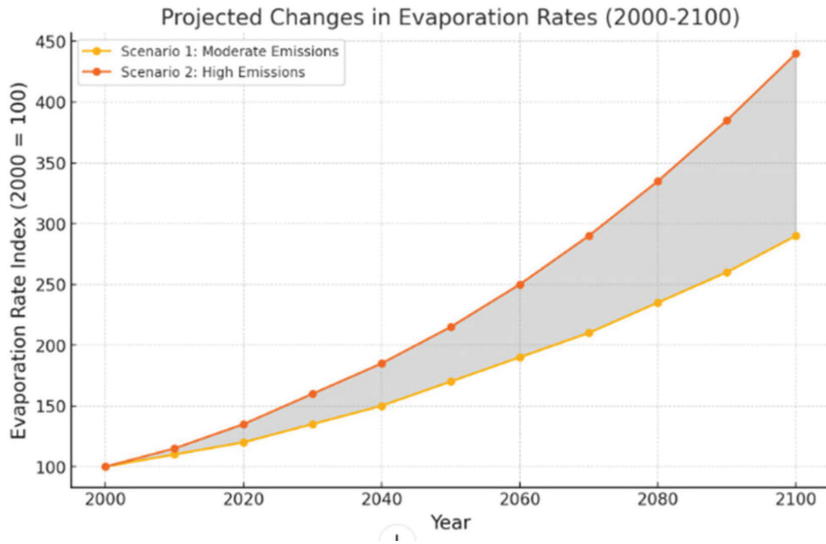


FIGURE 13.1 Impact of temperature rise on global average evaporation rate trends (2000–2100).

13.3.1.2 Temperature rise

Rising global temperatures affect the hydrological cycle in several ways. Higher temperatures increase evaporation rates from water bodies and soil, as well as transpiration from plants, which can lead to reduced soil moisture. Additionally, warming accelerates snowmelt, altering river flow patterns and impacting water availability throughout the year. These changes can disrupt water supply systems and affect agricultural and ecological systems.

Figure 13.1 illustrates the projected changes in evaporation rates from 2000 to 2100, modeled under two distinct greenhouse gas emission scenarios. It highlights the increasing trend due to rising global temperatures and climate change, with significant acceleration toward the latter half of the 21st century. The moderate emissions scenario shows a steady increase in evaporation rates, while the high emissions scenario predicts a more significant rise, reflecting the impact of increased global temperatures on the hydrological cycle. The shaded area between the two scenarios represents the range of potential outcomes depending on emission levels.

Rising temperatures due to climate change can alter the physical and chemical properties of water bodies. Warmer water temperatures can decrease dissolved oxygen levels, which are crucial for the survival of aquatic life. Lower oxygen levels can lead to hypoxia, which stresses or kills fish and other aquatic organisms [30]. Additionally, higher temperatures can accelerate the growth of harmful algal blooms, such as cyanobacteria, which produce toxins that can contaminate drinking water supplies and harm aquatic ecosystems [31]. Increased temperatures can also enhance the rate of chemical reactions, potentially leading to higher concentrations of pollutants such as nitrates and heavy metals in water bodies [32].

13.3.1.2.1 Changes in soil moisture and the hydrological cycle

Rising temperatures have a profound impact on soil moisture and the overall hydrological cycle. Increased temperatures accelerate the rate of evaporation from land surfaces and bodies of water, leading to drier soil conditions. This reduction in soil moisture can exacerbate drought conditions and negatively affect agricultural productivity, particularly in already arid regions. Additionally, warmer temperatures can lead to earlier snowmelt, altering the timing and magnitude of river flows. This shift can disrupt water availability for ecosystems and human use, especially during critical growing seasons. The changes in soil moisture and hydrological processes necessitate adaptive water management strategies to mitigate the

impacts of climate change on water resources. The amount of water held in global soils is a minuscule fraction of Earth’s total water, constituting only about 0.001%. While this may seem negligible compared to the vast quantities of water in oceans (97.5%), glaciers and ice caps (1.74%), and groundwater (1.7%), soil moisture plays a crucial role in the Earth’s hydrological cycle. It influences processes such as evaporation, infiltration, and groundwater recharge and has significant implications for agriculture, weather patterns, and climate. Despite its small proportion, soil moisture is vital for managing water resources and understanding local and regional environmental dynamics.

13.3.1.3 Extreme weather events

Climate change contributes to a higher frequency and severity of extreme weather events such as droughts, floods, and storms. These events can significantly impact water quality by increasing the amount of pollutants and sediments entering water bodies. Moreover, extreme weather can strain water management infrastructure, potentially leading to failures in water distribution and treatment systems [33].

- a. **Increased risks of waterborne diseases and contamination:** Temperature changes and extreme events also heighten the risk of waterborne diseases. Warmer temperatures can promote the growth of pathogens such as bacteria, viruses, and parasites in water supplies, increasing the likelihood of waterborne disease outbreaks [34]. Extreme weather events can exacerbate these risks by contaminating water sources with fecal matter and other pollutants during floods, leading to higher incidences of diseases such as cholera, giardiasis, and cryptosporidiosis [35]. Additionally, the damage to water infrastructure caused by extreme events can lead to disruptions in water treatment and distribution, further increasing the risk of contamination and disease transmission [36].

Figure 13.2 shows the increasing frequency of extreme weather events over four decades. The rise in the number of droughts, floods, and storms underscores the growing impact of

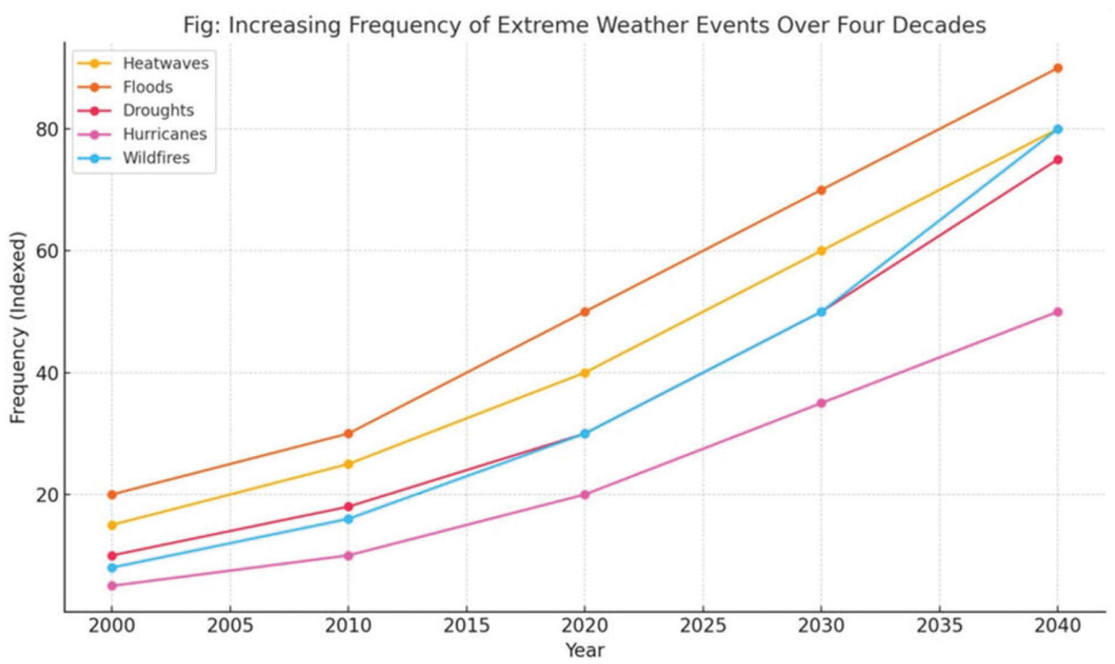


FIGURE 13.2 Trends in extreme weather events over the past 40 years.

climate change on water quality and infrastructure. The increasing frequency of these events has significant implications for water management, infrastructure resilience, and disaster preparedness. More frequent droughts can lead to water shortages and agricultural stress, while increased floods and storms pose risks to human life, property, and ecosystems.

- b. **Implications for water quality and infrastructure:** Extreme weather events, such as heavy rainfall, droughts, and heat waves, have significant implications for both water quality and infrastructure. Heavy rainfall and flooding can lead to increased runoff that carries pollutants like pesticides, fertilizers, and industrial chemicals into water bodies, thereby deteriorating water quality [37]. Floods can also overwhelm sewage systems and water treatment plants, resulting in the discharge of untreated or inadequately treated wastewater [38]. Conversely, prolonged droughts can concentrate pollutants in dwindling water sources, leading to higher contaminant concentrations [39]. Additionally, heatwaves can exacerbate the growth of harmful algal blooms in freshwater systems, which produce toxins harmful to both aquatic life and human health [40].

The impact on water infrastructure is equally critical. Extreme weather events can cause substantial damage to infrastructure such as pipelines, reservoirs, and treatment facilities. Flooding and storms often lead to costly repairs and replacement needs, while heat waves can result in infrastructure failures due to material stress and increased wear [41]. Furthermore, these events can strain the operational capacity of water systems, leading to service disruptions and delays in maintenance and repair [42]. To mitigate these impacts, it is essential to upgrade infrastructure to enhance resilience and develop robust emergency response plans [43]. Ensuring that water systems are adaptable to extreme weather conditions can help safeguard both water quality and infrastructure against future challenges.

13.4 IMPACT OF EXTREME WEATHER EVENTS ON HYDROLOGY

13.4.1 Impact of Heavy Rainfall on Water Quality

Heavy rainfall can have a substantial impact on water quality, especially in areas with inadequate drainage or high levels of pollutants. During heavy rainfall, significant amounts of water swiftly wash off the land, transporting sediments, nutrients, and pollutants including fertilizers, pesticides, and waste into rivers, lakes, and coastal waterways. This runoff can lead to the contamination of water bodies, increase turbidity, and lower oxygen levels, negatively impacting aquatic ecosystems and diminishing the availability of clean water for human consumption. Each of these effects is explained individually below.

- i. **Increased runoff and contaminant transport:** Heavy rainfall leads to increased surface runoff, which carries pollutants from land surfaces into water bodies. This runoff can include agricultural chemicals (pesticides and fertilizers), industrial pollutants, and waste from urban areas. The result is elevated levels of contaminants such as nitrates, phosphates, and heavy metals in rivers, lakes, and coastal waters. The increased nutrient load can cause eutrophication, leading to harmful algal blooms and degraded aquatic ecosystems [44].
- ii. **Flooding and infrastructure damage:** Intense rainfall can cause flooding, which disrupts wastewater treatment facilities and sewage systems. Overwhelmed systems may release untreated or partially treated wastewater into water bodies, contributing to high levels of pathogens and other pollutants. This can significantly impact water quality, posing risks to public health and the environment. Floodwaters can also erode soil and deposit sediments into

aquatic systems, further affecting water quality [45]. The study finds that flooding significantly contributes to the degradation of water quality in urban areas. During flood events, contaminants such as heavy metals, pathogens, and nutrients are washed into water bodies, leading to elevated levels of pollution. For example, levels of heavy metals like lead (Pb) and cadmium (Cd) were observed to increase by 50%–70% in urban waterways after flood events. *E. coli* and other fecal coliform bacteria, spiked dramatically, with counts exceeding 10,000 CFU/100 mL in some cases, far surpassing safe drinking water standards. Floodwaters contributed to an influx of nutrients such as nitrogen (N) and phosphorus (P). The study reported a 30%–50% increase in total nitrogen (TN) and total phosphorus (TP) concentrations in affected water bodies. Following a flood, turbidity levels increased by up to 200 NTU (Nephelometric Turbidity Units), and total suspended solids (TSS) rose to 300–500 mg/L, indicating a sharp decline in water clarity. Biochemical Oxygen Demand (BOD) levels, which measure the amount of oxygen consumed by bacteria in decomposing organic matter, were found to increase from baseline levels of 3–5 to 10–15 mg/L post-flood, indicating higher organic pollution. This nutrient surge often led to eutrophication in urban water systems, promoting algal blooms and reducing dissolved oxygen levels, thereby harming aquatic life.

- iii. **Increased turbidity and sediment load:** Heavy rainfall can lead to increased sediment transport into rivers and lakes. The higher sediment load results in increased turbidity, which reduces light penetration and affects aquatic plant growth. This can alter aquatic habitats and reduce the quality of drinking water [46]. The research identifies soil erosion as a significant source of sediment in water bodies. Poor land management practices, deforestation, and construction activities are noted as primary contributors to increased sediment load. The accumulation of sediments can also impact the operation of water treatment facilities by clogging filters and increasing maintenance needs. The studies of Williams et al. [47] revealed that sediments, including silt, clay, and organic matter, can clog filters, reduce the efficiency of chemical treatment processes, and increase the wear and tear on equipment. Facilities with high sediment loads face increased maintenance requirements. The research found that facilities dealing with high sediment content required 20%–30% more frequent filter replacements and 50% more frequent backwashing of filtration systems compared to those with lower sediment levels. High turbidity caused by sediments can hinder the effectiveness of disinfection processes, particularly ultraviolet (UV) treatment. The study reported that facilities with high sediment loads experienced a 15%–20% reduction in UV disinfection efficiency due to the scattering and absorption of UV light by suspended particles. The research emphasizes the importance of infrastructure adaptations to manage sediment loads effectively. These adaptations include the installation of sedimentation basins, advanced filtration systems, and regular dredging of water intakes to reduce the sediment entering treatment facilities.
- iv. **Disruption of natural water cycling:** Climate change-induced alterations in rainfall patterns can significantly disrupt natural water cycles, leading to several critical impacts. These include changes in the timing and magnitude of river flows, which affect water availability and complicate water management. The irregularity in water cycles can also undermine the reliability of water supplies, potentially leading to shortages or excesses at different times of the year. Additionally, increased runoff and flooding due to heavy rainfall heighten the risk of waterborne diseases, especially in regions with inadequate water treatment infrastructure. Addressing these challenges is essential for developing adaptive strategies to ensure sustainable water management in the face of climate change [48,49].
- v. **Global variability:** The impact of heavy rainfall on water quality varies regionally. In tropical and subtropical regions, where intense rainfall and frequent flooding are common, the effects on water quality can be more pronounced compared to temperate regions. In contrast, arid and semi-arid regions might experience different challenges, such as infrequent but intense rainfall events that lead to sudden spikes in runoff and contaminant loads.

13.4.2 Impact of Droughts on Hydrology and Infrastructure

Droughts have profound effects on both hydrological systems and infrastructure, posing significant challenges to water resources and management. One of the primary impacts of droughts is the reduction in water availability. Decreased precipitation and lower groundwater recharge result in reduced streamflow in rivers and diminished groundwater levels. This strain on water supply systems can lead to shortages for urban, agricultural, and industrial uses, necessitating water rationing and potentially increasing water costs. Additionally, lower water levels can concentrate contaminants in water bodies, worsening water quality and straining treatment facilities [50].

Gosling et al. [51] found that river flow reductions during severe droughts can reach up to 40% below average levels. For example, during the 2010–2012 drought in the European Union, river flows decreased by approximately 30% in some regions. During the 2014–2015 drought in Brazil, the level of the Cantareira reservoir, which supplies water to São Paulo, fell to 6% of its total capacity. Reservoir storage in the western United States decreased by 20%–30% during drought years from 2000 to 2015. In Spain, agricultural water use increased by 30% during the 2005–2008 drought compared to normal years, leading to significant declines in available water for other uses.

Droughts also alter hydrological patterns, affecting runoff and the timing and magnitude of river flows. This disruption can impact water availability throughout the year, with significant effects on reservoir storage and hydropower generation [52,53]. Moreover, reduced precipitation can decrease water levels in wetlands and lakes, affecting biodiversity and ecosystem services [54].

Infrastructure is not immune to the impacts of drought. Prolonged low water levels can lead to the deterioration of water infrastructure, such as pipelines and reservoirs, due to increased stress and reduced flow [55]. The need for more frequent maintenance and repairs can drive up operational costs. Additionally, the increased concentration of contaminants can necessitate more intensive water treatment processes, further straining existing infrastructure.

Economically, droughts can cause significant agricultural losses often by 30%–60% or more by reducing crop yields and livestock production, leading to increased food. In severe droughts, livestock losses can reach 20%–50% of the total herd, impacting rural economies that rely heavily on animal husbandry. Estimates from various sources might show that the economic impact of drought on agriculture can range from \$1 billion to \$5 billion per year in affected regions. During severe droughts, rural-to-urban migration can increase by 20%–50%, as people seek alternative livelihoods and resources. The costs associated with managing and securing water supplies during drought conditions can strain municipal budgets, potentially leading to higher water rates for consumers [56]. Socially, water shortages can disrupt daily life and lead to conflicts over resources, impacting community health and quality of life. Projections indicate that by mid-century, regions like southern Europe and parts of South America could experience water availability reductions of up to 50% under extreme drought scenarios.

13.4.3 Impact of Storms on Hydrology

Storms have a profound impact on hydrology, influencing various aspects of water systems and their management. Intense rainfall from storms can lead to rapid increases in runoff, which may overwhelm rivers, streams, and drainage systems, resulting in flash floods and elevated water levels. This sudden surge in water can cause significant erosion, sediment transport, and changes in stream morphology, impacting aquatic habitats and potentially leading to the degradation of water quality. The high volume of runoff can also lead to the overflow of water bodies, contaminating drinking water sources with pollutants from urban and agricultural areas. Furthermore, storms can disrupt groundwater recharge processes. While heavy rainfall can temporarily boost groundwater levels, the rapid runoff may reduce the infiltration rate, limiting the long-term replenishment of aquifers. In their 2018 study, Gao et al. [57] investigated the effects of extreme storm events on sediment load and river quality, revealing several key findings.

They observed a significant increase in sediment loads during extreme storms, with peak values ranging from 500 to 1,500 mg/L compared to baseline levels of around 200 mg/L. Similarly, turbidity surged to up to 75 NTU during storms, whereas normal conditions showed turbidity levels around 10 NTU. TSS rose to 1,200 mg/L during storms, a stark contrast to typical levels of 150 mg/L. Nutrient concentrations also spiked, with nitrate levels increasing from 1.5 to 4.0 mg/L and phosphorus rising from 0.2 to 1.0 mg/L.

In their 2017 review, Liu et al. [58] provide detailed data on storm water runoff and pollution, highlighting significant findings. The study reports that heavy metals such as zinc and lead are commonly present in storm water, with concentrations ranging from 100 to 800 µg/L for zinc and 10–50 µg/L for lead, depending on land use and storm intensity. Nutrient levels, particularly nitrogen and phosphorus, can also be substantial, with nitrogen concentrations varying from 2 to 10 mg/L and phosphorus ranging from 0.5 to 5 mg/L during storm events. The review further notes that particle-bound pollutants, such as sediment, can be transported at rates from 0.5 to 10 kg/ha per storm event, with higher loads observed in areas with more impervious surfaces. Data shows that a 1-hour storm with 50 mm of rainfall can produce runoff volumes of 20–40 mm in urban areas, depending on imperviousness and land use.

The effectiveness of best management practices (BMPs) is also detailed. Green infrastructure measures like rain gardens and green roofs can reduce runoff volume by up to 60% and remove 50%–70% of suspended solids and nutrients. Retention basins, on the other hand, can capture 70%–80% of storm water runoff and remove up to 60% of TSS and 40% of nutrients, though their performance varies with design and maintenance.

13.4.4 Impact of Sea-Level Rise and Saltwater Intrusion on Hydrology

Climate change-induced sea-level rise has a profound influence on coastal aquifers and groundwater resources. Saltwater intrusion, caused by rising sea levels and excessive groundwater extraction, has an impact on hydrology by polluting freshwater aquifers with saline water. This limits the availability of fresh groundwater for drinking and irrigation, raises salinity levels in rivers and wetlands, and alters natural water balance, hurting ecosystems and causing water table changes. Saltwater intrusion affects drinking water supplies in several ways.

- i. **Contamination of freshwater sources:** Increased salinity levels from intrusion of saltwater into coastal aquifers risk groundwater's sustainability for agricultural and human use. Saltwater from nearby marine ecosystems can permeate the aquifer system when the flow rate of freshwater decreases as a result of excessive extraction of groundwater or sea-level rises. Water quality declines with increasing salinity levels, resulting in it being unsuitable for both drinking and irrigation. This demands expensive, energy-intensive, and economically costly measures like desalination. As an alternative, towns could have to improve their infrastructure for water purification or explore new sources of freshwater, either of which could lead to substantial logistical and economic challenges. Dillon et al. [59] elucidate that groundwater recharge rates, which are vital in mitigating such intrusion, are influenced by various factors including the type of aquifer (e.g., unconfined or confined), land use patterns (e.g., urban development or agricultural practices), and regional geographic characteristics. Their findings underscore the necessity of tailored groundwater management strategies to address these challenges effectively.
- ii. **Impact on water quality:** Coastal water bodies can experience considerable quality degradation due to the intrusion of saltwater into nearby aquifers. This phenomenon leads to increased salinity levels, which disrupts freshwater ecosystems and may result in a decline of aquatic species that cannot adapt to the heightened salinity [60]. The health of aquatic communities is adversely affected by this ecological disruption, which also threatens biodiversity. Additionally, as salinity levels rise, more advanced and expensive treatment solutions become necessary to

comply with water quality standards, owing to the elevated concentrations of total dissolved solids (TDS) and chlorides. Traditional treatment methods often prove inadequate for managing high salinity, which complicates the situation further.

iii. **Economic and social consequences:** In areas where groundwater is the main source of water for homes, farms, and industries, saltwater intrusion can lead to serious financial problems [61,62]. Highlight the urgent need for effective strategies to address the various impacts of saltwater intrusion. It is essential to improve water treatment plants to manage higher salt levels, create new water delivery systems, and build infrastructure to stop further saltwater mixing. These costs can strain local economies, especially in places with limited financial resources. In addition to these direct expenses, reduced agricultural yields and increased prices for other water sources also affect local economies. Communities may face social challenges in their everyday lives.

iv. **Strategies for preventing saltwater intrusion into coastal aquifers:**

- Preventing saltwater intrusion into coastal aquifers requires a combination of techniques aimed at preserving groundwater levels and erecting barriers against saltwater intrusion. [63–65].
- Managed aquifer recharge (MAR) is a method for increasing groundwater levels and counteracting saltwater pressure by replenishing aquifers with water through injection wells or infiltration basins.
- A second crucial tactic is to reduce groundwater pumping in coastal areas in order to lower the hydraulic gradient that draws saltwater inland.
- Subterranean barriers, such as impermeable walls, can be built to keep saltwater out of freshwater.
- A buffer zone formed by strategically placed freshwater injection can stop saltwater advancement if freshwater is available on a regular basis.
- Natural groundwater recharge can be improved by appropriate land use management. The goal is to protect wetlands and build with permeable materials.

13.5 ADAPTATION AND MITIGATION STRATEGIES

Hydrological adaptation and mitigation techniques are aimed at tackling the effects of climate change on water supplies. Adaptation entails changing water management strategies to cope with changes such as altered rainfall patterns, increasing droughts, and flooding, while also improving the resilience of water systems. Mitigation measures aim to reduce the factors that contribute to these changes, such as lowering water-related carbon emissions through sustainable water management, conservation, and ecosystem restoration. These measures are critical to ensuring water supply and quality in the face of climate change.

13.5.1 Water Management: Integrated Water Resources Management

IWRM is a holistic planning approach that encourages the collaborative development and administration of water, land, and associated resources. The main goal of IWRM is to enhance economic and social well-being while ensuring the long-term viability of crucial ecosystems. As it integrates many aspects of water management, including environmental, economic, and social aspects, this strategy is especially useful in tackling the intricate and interrelated problems presented by climate change on water resources.

TABLE 13.2 Fundamental Principles of Integrated Water Resources Management (IWRM)

<i>PRINCIPLE</i>	<i>DESCRIPTION</i>	<i>BENEFITS</i>	<i>CITATIONS</i>
Holistic approach	Coordinates surface water, groundwater, and ecological well-being in wastewater management	Guarantees thorough administration of water supplies	Global Water Partnership [67]
Stakeholder participation	Involves all relevant stakeholders in decision-making processes	Enhances transparency, inclusiveness, and local ownership.	Pahl-Wostl [68]
Integrated decision-making	Coordinates policies and actions across different sectors and levels of government	Promotes coherence in water management strategies and avoids conflicts	Biswas [69]
Sustainable development	Strives to achieve a harmonious equilibrium between the environmental, economic, and social requirements of both the present and the future	Ensures the availability and sustainable quality of water resources for future usage	Duda et al. [70]
Water quality management	Focuses on maintaining and improving water quality to protect human health and ecosystems	Reduces pollution, protects aquatic life, and ensures safe water for consumption	Davies [71]
Adaptive management	Utilizes a flexible approach that can adjust to new information and changing conditions	Enhances resilience to uncertainties and dynamic conditions	Holling [72]
Ecosystem-based management	Incorporates the health of ecosystems in water management practices	Promotes ecosystem services and biodiversity conservation	Baron et al. [73]
Equity and fairness	Ensures that water resources are distributed fairly among different groups and regions	Addresses social inequalities and promotes social justice in water access	UNDP [74]

The framework of IWRM is crucial for developing strategies that can effectively cope with climatic variability and change, especially in dealing with severe weather phenomena like floods and droughts. Through the integration of hydrological data with climate modeling, IWRM enables the strategic planning of future water supply and evaluates the possible effects on various sectors. Additionally, IWRM encourages the implementation of several mitigating measures, including the use of water-saving technology, improving watershed management to reduce greenhouse gas emissions, and boosting water use efficiency. By incorporating these mitigation strategies into water management practices, IWRM helps to reduce the effects of climate change at both local and global scales [66]. Table 13.2 outlines the fundamental principles of IWRM, emphasizing the coordinated development and management of water, land, and related resources to maximize economic and social welfare without compromising the sustainability of vital ecosystems.

13.5.2 Sustainable Water Use Practices and Demand Management

- a. **Sustainable water use practices:** Sustainable water use practices are crucial for adapting to climate change and mitigating its effects on water resources. Table 13.3 presents widely recognized sustainable water practices, supported by scientific evidence, emphasizing their role in conserving water and preserving ecological balance.

TABLE 13.3 Sustainable Water Use Practices

<i>PRACTICE</i>	<i>DESCRIPTION</i>	<i>METHODS</i>	<i>BENEFITS</i>	<i>CITATIONS</i>
Water conservation	Reducing water use through efficiency measures	Low-flow fixtures, leak detection, water-efficient appliances	Reduces water consumption, lowers utility bills	Gleick [75]
Rainwater harvesting	Collecting and storing rainwater for later use	Rain barrels, cisterns, rooftop collection systems	Provides an alternative water source and reduces demand on municipal supply.	Siegenthaler et al. [76]
Greywater recycling	Reusing wastewater from sinks, showers, and laundry	Filtration, biological treatment systems. Industrial Water Reuse	Reduces potable water demand, recycles water for non-potable uses	Lazarova et al., [77]
Water-efficient landscaping	Designing landscapes that require minimal irrigation	Xeriscaping, use of drought-tolerant plants	Reduces water use in irrigation, lowers maintenance costs	Miller [78]
Leak detection and repair	Identifying and fixing leaks in water supply systems	Acoustic sensors, pressure testing	Prevents water loss, reduces operational costs	Hannum et al. [79]
Efficient irrigation systems	Using advanced technologies for irrigation	Drip irrigation, Sprinkler Irrigation, smart controllers, soil moisture sensors.	Optimizes water use for agriculture, minimizes waste	Hanson et al. [80]
Water recycling and reuse	Treating and reusing water for multiple purposes	Secondary and tertiary treatment processes	Reduces freshwater demand, minimizes wastewater discharge	Liu and Zhang [81]
Sustainable water management	Managing water resources to meet current and future needs	Integrated Water Resources Management (IWRM), water audits	Balances water supply with demand and ensures long-term sustainability	Murphy and Coleman [82]

Demand management strategies: Demand management is equally essential for addressing the challenges of water scarcity. The following strategies are backed by scientific data demonstrating their effectiveness. Table 13.4 summarizes the citations for each of the water management strategies mentioned.

13.5.3 Adaptation and Mitigation Strategies: Technological Innovations

Adaptation and mitigation techniques including technological advances concentrate on creating and deploying cutting-edge solutions such as renewable energy technology, smart water management systems, and climate-resilient infrastructure. By combining these advancements, we will be able to better adapt to changing environmental conditions and lessen the effects of climate change.

TABLE 13.4 Demand Water Management Strategies

<i>STRATEGY</i>	<i>DETAILS</i>	<i>CITATION</i>
Tiered water pricing	Implementing tiered water pricing can lead to a 10%–20% reduction in household water consumption	Grafton and Ward [83]
Subsidies for water-efficient appliances	Providing subsidies can reduce household water use by up to 35	Grafton and Liu [84]
Public awareness and education campaigns	Educational campaigns can reduce water use by 5%–10% through behavioral changes	O’Keefe and Van Houtven [85] and Dolnicar and Hurlimann [86]
Leak detection and repair programs	Leakages account for 10%–30% of total water losses. Regular programs can reduce these losses by up to 50%	Vamvakeridou-Lyroudia and Kapelan [87] and Tricarico and Iannuzzi [88]
Water use restrictions	Temporary restrictions during droughts can reduce water consumption by 15%–25%	Hanak and Schlenker [89]

13.5.4 Advances in Water-Saving Technologies, Desalination, and Wastewater Reuse

Technological innovations play a crucial role in both adapting to and mitigating the effects of climate change on water resources. Advances in water-saving technologies, desalination, and wastewater reuse have the potential to significantly reduce water scarcity and improve water management.

13.5.4.1 Water-saving technologies

Table 13.5 summarizes various water-saving technologies along with their journal citations.

13.5.4.2 Desalination technologies

Desalination plants are facilities that convert seawater or brackish water into freshwater by removing salt and other impurities. These plants help solve water shortages by supplying a reliable source of safe drinking water in places where natural freshwater is scarce. Prominent desalination methods include reverse osmosis (RO), which uses high-pressure membranes to filter out salt, and multi-effect distillation (MED), which relies on heat to evaporate and then condense water [95]. As water needs grow, desalination is becoming increasingly important, especially in dry areas. Desalination plants use various technologies to convert seawater or brackish water into freshwater. The most widely used method is RO, which accounts for about 60% of global desalination capacity. Recent advancements in membrane technology have improved RO efficiency, reducing energy consumption by 20%–30% over the past decade [96]. Modern RO systems using solar-powered RO currently use 2.5–4 kWh per cubic meter of water, compared to 6 kWh in older systems [97,98]. Desalination technologies offer various methods for producing freshwater with differing efficiencies and energy requirements. (a) RO stands out as the most prevalent technique, utilizing a semi-permeable membrane to effectively extract salt from water. This method boasts an efficiency range of 40%–60% while consuming between 3 and 7 kWh for every cubic meter processed. The brine produced is generally managed through deep well injection or discharged into surface waters, making it suitable for both drinking water and industrial uses [84]. (b) MED operates through several stages of evaporation and condensation, achieving a higher efficiency of 70%–85% with an energy requirement of 5–10 kWh per cubic meter. This technique often resorts to seawater dilution or evaporation ponds for brine disposal and is mainly employed in large industrial operations [99]. (c) Multi-stage flash distillation (MSF) works by boiling seawater at progressively lower pressures

TABLE 13.5 Water-Saving Technologies

TECHNOLOGY	DETAILS	REFERENCES
Low-flow fixtures	Installing low-flow fixtures can reduce water use in households by up to 50%	Borenstein and Johnson [90]
Rainwater harvesting systems	Collecting and using rainwater can reduce potable water use by up to 40% in some regions	Torkil and El-Sadek [91]
Greywater recycling	Reusing greywater for irrigation and other non-potable uses can save up to 30% of household water	Nelson and White [92]
Smart irrigation systems	Smart irrigation systems adjust water use based on real-time weather data and soil moisture, saving 20%–50% of water	Su and Chen [93]
Water-efficient appliances	Using water-efficient appliances, such as dishwashers and washing machines, can reduce water use by up to 35%	Fletcher and Houghton [94]

across multiple stages, yielding an efficiency of 60%–75% and consuming 7–15 kWh per cubic meter. The brine is typically diluted or discharged, and MSF is frequently found in extensive desalination facilities [100]. (d) Electrodialysis (ED) harnesses electrical potential to facilitate ion exchange through selective membranes, achieving an efficiency of 40%–60% with an energy consumption of 2–5 kWh per cubic meter. The brine from ED systems is usually released into marine environments, and this technology is primarily used for desalinating brackish water [101]. (e) Nanofiltration (NF) operates similarly to RO but features larger pore sizes, allowing certain monovalent ions to pass through. It achieves an efficiency of 50%–70% while consuming 1–3 kWh per cubic meter. Brine disposal methods can vary by facility, and NF is often utilized for water softening and treatment [102]. (f) Forward osmosis (FO) employs an osmotic pressure gradient to draw water through a semi-permeable membrane, achieving an efficiency of 30%–50% with a low energy consumption of 0.5–2 kWh per cubic meter. The methods for brine disposal depend on the specific system design, and FO is emerging as a promising technology for producing potable water [103].

13.5.4.3 Wastewater reuse technologies

Wastewater reuse technologies are critical to sustainable water management because they treat and repurpose wastewater for a variety of applications. Each technique has various benefits and drawbacks, depending on its efficiency, common uses, and treatment processes.

(a) **Greywater Recycling** involves the reuse of relatively clean wastewater from sources such as sinks and showers, achieving 70%–90% efficiency. It is commonly used for irrigation, toilet flushing, and cooling systems, and involves filtration and biological treatment processes. Pathogen clearance and chemical pollution pose significant obstacles [104,105]. (b) **Blackwater Treatment** addresses wastewater from toilets with high organic load, achieving 60%–85% efficiency. It is utilized for agricultural irrigation and industrial purposes, involving primary, secondary, and tertiary treatment stages. Major challenges include high energy demands and maintenance costs [106,107]. (c) **Constructed Wetlands** utilize natural wetland processes for wastewater treatment, achieving 70%–85% efficiency. This method is applied to landscape irrigation and habitat restoration and includes sedimentation, filtration, and biological treatment. Challenges include space requirements and slower treatment rates [108,109]. (d) **Membrane Bioreactors (MBRs)** combine biological treatment with membrane filtration, reaching 80%–90% efficiency. They are used for municipal and industrial wastewater reuse but come with high capital and operational costs [110,111]. (e) **RO** employs a semi-permeable membrane to remove contaminants, with an efficiency of 90%–99%. It is mainly used for producing potable and high-quality industrial water,

involving pre-treatment and membrane filtration. Challenges include high energy consumption and brine disposal [112,113]. (f) **Advanced Oxidation Processes (AOPs)** AOPs employ chemical oxidants such as ozone or hydrogen peroxide in conjunction with ultraviolet radiation or catalysts to facilitate the degradation of organic pollutants in wastewater. These processes are particularly proficient in eliminating pharmaceutical residues and other emerging contaminants that conventional treatment techniques often fail to address. This method is employed in potable water production and various industrial processes and involves chemical oxidation and filtration. Challenges include high operational costs and complex management requirements [114,115].

13.5.5 Role of Remote Sensing and Modeling in Water Resource Management

Remote sensing and modeling technologies are integral to modern water resource management, enabling better monitoring, planning, and decision-making in the face of climate change.

13.5.5.1 Remote sensing

Remote sensing provides an efficient method for monitoring and managing water resources on a wide scale. It is essential for many elements of water management, such as monitoring bodies of water, analyzing water quality, monitoring floods and droughts, and mapping. Satellites with sensors operating at different wavelengths (optical, infrared, microwave, etc.) inculcate vital information with regard to water resources, namely precipitation, soil moisture, snow, and water surface. For example, the NASA GRACE (Gravity Recovery and Climate Experiment) Satellites are used to observe global trends in groundwater depletion. High-resolution cameras and sensors mounted on drones and Unmanned Aerial Vehicle give localized information about water resources. These instruments are particularly effective in observing irrigation networks, establishing agricultural water deficit, and detecting breaches in water supply networks. (a) Remote sensing technologies, such as satellite images and aerial photography, are critical for monitoring changes in surface water bodies, giving large-scale, frequent updates on water levels and quality [116]. (b) Technologies such as Moderate Resolution Imaging Spectroradiometer, Landsat, and Sentinel satellites enable the monitoring of water quality metrics such as chlorophyll-a and turbidity, allowing for assessments across large areas and aiding in the detection of pollution sources, hence improving water quality management [117]. (c) Remote sensing tools such as radar and optical images, when paired with precipitation data, may identify and predict flood and drought conditions, providing early warnings that can assist disaster management and mitigation efforts [118]. (d) GIS combined with remote sensing data helps generate detailed maps of watersheds and river basins, which are helpful in spatial evaluation, land use planning, and resource allocation [119]. (e) Evaluating temporal remote sensing data allows for the identification of variations in land use and vegetation diversity, that is essential for understanding the effects of climate variability and urbanization [120]. These applications showcase the value of remote sensing in effectively managing water reserves over wide geographic areas.

13.5.5.2 Modeling

Modeling enhances remote sensing by simulating numerous facets of water resource management and making data-driven forecasts. (a) Climate and Integrated Water Resources models are vital in the simulation of water in movement, distribution in the hydrological circle, and quality. Climate change impact and water resource management can be predicted and mitigated through these models. For instance, there are climate-hydrological models like the Soil and Water Assessment Tool (SWAT) and HEC-HMS that analyze water movement, distribution, and quality, which helps us understand hydrological processes and estimate water flow under various circumstances [121]. These models are applied

to evaluate the impacts of land use and climate change on watershed hydrology and water quality. Hydrological-economic-environmental models, on the other hand, are integrated water resource models that seek to advance the rational utilization of water in many sectors. It elucidates these models aiding policymakers in evaluating disparities in water requirements for diverse sectors such as irrigation, industries, and urban development. (b) Water quality models like QUAL2K and CE-QUAL-W2 forecast the fate and transport of contaminants, allowing for the study of water quality trends as well as the assessment of pollution sources and their effects [122]. (c) Coupled climate-hydrology models are used to examine climate change's impact on water supplies. These models help with long-term planning and adaptation strategies by examining different climatic scenarios [123]. (d) For water demand forecasting and supply modeling and evaluation, statistical models as well as system dynamics models are employed. This helps in infrastructure planning and efficient water management [124]. (e) The IWRM approaches and models presented here, are based on the cooperation of the hydrological, environmental, and social components for the purpose of water resources management. These models enhance the understanding of water management problems and their solutions [125].

13.6 ADAPTATION AND MITIGATION STRATEGIES: POLICY AND GOVERNANCE

13.6.1 Need for Climate-Resilient Water Policies and Regulations

Global warming presents some of the major complexities in water supply and demand and therefore calls for stakeholders to formulate policies and regulations that are tolerant to climatic changes. These policies should take into consideration the growing instability in water supply, risks posed by severe storms and other climate change occurrences, and water source sustainability [126].

Accommodating climate projections is essential for improving water system vulnerability. Adaptive Water Management Frameworks work under the flexibility that climate has in terms of projections in order to guarantee that policies are still beneficial despite the uncertainty that may exist in the future [127]. For example, Australia's National Water Initiative under the water resource plan is on climate change adaptations [128]. Drought and Flood Management Plans play a big role toward Climate Resilience because they incorporate conservation of water, flood control measures, and Insurance instruments to prevent the impacts of climate hazards. As the Water Framework Directive of the European Union has been focused on here, members of the Union are mandated to integrate climate adaptation into the River Basin Management Plans.

13.6.2 Strengthening Regulatory Frameworks

Strategies for enhancing governance of water resources to address climate change impacts include enhancing regulatory frameworks. The significance of pollution danger by extreme weather occurrences calls for the enhancement of Water Quality Standards and Pollution Control [129]. Situations that alter the quantities, qualities, or sources of pollutants include stricter rules on industrial discharges and agricultural and urban wastewater, as explained by the United States Clean Water Act [130]. The management of water resources requires governance because water is shared across international borders thus the need for Transboundary Water Management. Some solutions for climate change, such as the Nile Basin Initiative, involve other countries and help countries adapt which are sharing water resources [131,132].

13.6.3 Community-Based Adaptation Approaches and Stakeholder Engagement

Climate change adaptation entails a variety of approaches that encourage community participation and inclusivity in water management. There are two major methods of adaptation measures: community-based adaptation (CBA) and stakeholder engagement. These categories are critical for the optimal use of water resources and the development of resistance at the local, regional, and transboundary levels.

- a. **CBA approaches:** These strategies are based on the principle of ensuring that local community knowledge, requirement, and potential are included in the adaptation process. CBA is even more efficient in tackling water management issues at the community level. For instance, through Community-Based Water Monitorings of water; in Nepal, there has been an increased ability to adapt to climate change through enhanced storage facilities, the diversification of water sources, and a modification of conventional irrigation techniques [133]. In this process, affected stakeholders are involved in planning implementation, making sure that the adaptation strategies to be adopted are culturally appropriate and socially acceptable. In Tanzania, a study showed that the use of issued based-watershed management planning that entails the local farmers giving their input in the conservation of their soil and water enhanced a better approach in combating the effects of climate change [134].
- b. **Stakeholder engagement:** IWRM requires the engagement of multiple stakeholders including government departments, non-governmental organizations, private organizations, and the public. Knowledge acquisition, sharing, goal harmonization, and resource mobilization occur in these platforms, thus enhancing the development of more suitable adaptation measures. In this regard, the Mekong River Commission that brings together stakeholders from the countries within the Mekong River Basin is an example, supporting climate change adaptation in water management in the region [135]. It also has the support-building functions which are a necessity in the preparation of the stakeholders with the knowledge and skills needed for adaptation. Some of the Indian capacity-building measures contained in its National Water Mission are public education programs that help local governments and other stakeholder groups understand water-saving methods and other climate change mitigation measures [136].

13.7 FUTURE CHALLENGES AND RESEARCH NEEDS

The effects of climate change on water supply and demand are constantly being experienced across the world, yet significant knowledge deficits remain, which hinder adaptation and management programs. It is necessary to enhance water resource management particularly in sensitive environments, compliance with the above-mentioned gaps. Additional research is needed in the following key areas: (a) Climate Modeling: Climate models are useful for predicting the outcome of climate change; however, present-day climate models can fall short in providing an accurate representation of regional events such as monsoon and tropical cyclones. These localized climate events are of crucial significance to water resource management especially in the developing countries where regional climate models possess insufficient resolution [137]. (b) Impact Assessment: Comprehensive assessments of climate change's effects on water resources are scarce, notably for groundwater recharge, water quality, and ecosystem services. Understanding the long-term effects of climate change and the cumulative effects of human activities is critical for developing adaptive water management solutions [138]. (c) Water-Energy-Food Nexus: The interdependence of water, energy, and food systems is intricate, but study into this nexus is still in its early phases.

More research is needed to understand how changes in one area may affect others, leading to integrated and sustainable policy creation [139].

13.7.1 Emerging Trends and Future Directions in Hydrology and Water Resources

The fields of hydrology and water resource management are currently witnessing transformations driven by factors like changes, urbanization, and advancements in technology. There is a noticeable shift toward incorporating technology frameworks and interdisciplinary approaches to improve water management strategies. These new research areas aim to enhance forecasting abilities promote sustainable water resource use and address aspects of water governance. These efforts offer opportunities for innovation and adaptability, in tackling global challenges. Key future focus areas include.

- a. **Integrating data and machine learning:** Utilizing data and machine learning techniques is anticipated to enhance the analysis of large datasets collected from sensing and climate models. This will result in improved forecasts regarding water availability, flood risks, and drought occurrences [140,141].
- b. **Advancing water management:** There is an increasing emphasis on developing sustainable water management strategies such as infrastructure, decentralized systems, and urban planning. These efforts aim to address challenges in water resource management within environments and bolster resilience, against climate change [142].
- c. **Investigating hydro social interactions:** Research is delving into the relationship between systems and societies. It examines how water policies, governance and social factors influence water management practices and ensure fair distribution of resources [143].

The emerging areas of study hold promise, in expanding our understanding of resources as environmental and societal circumstances change. Upcoming research efforts will focus on developing strategies to tackle the impact of climate change on water resources. This entails enhancing models and investigating the long-term consequences of water cycles. We can expect a rise in interdisciplinary collaboration merging hydrology with fields such as social sciences, economics, and policy research [144–147]. The goal is to formulate comprehensive solutions, for intricate water management challenges.

13.8 CONCLUSION

Climate change has a significant impact on hydrology and water resources, leading to challenges such as unpredictable weather patterns, more frequent and severe extreme events like droughts and floods, and long-term shifts in water availability. Addressing these issues necessitates robust adaptation strategies that leverage advanced technologies, develop climate-resilient policies, and promote interdisciplinary research. Active community involvement and stakeholder engagement are crucial for crafting effective and inclusive water management practices. Despite ongoing research and policy initiatives, notable knowledge gaps remain in areas such as climate modeling, impact assessments, and understanding the complex interplay between water, energy, and food systems. To tackle these challenges, immediate and sustained action is required, including investment in new technologies, strengthening regulatory frameworks, and fostering collaborative approaches. This comprehensive strategy is essential for mitigating the impacts of climate change and ensuring water security, public health, and economic stability for future generations.

REFERENCES

- Dingman, S. L. (2015). *Physical Hydrology* (3rd ed.). Waveland Press.
- Kundzewicz, Z. W., Mata, L. J., Arnell, N. W., Döll, P., Kabat, P., Jiménez, B., Miller, K. A., Oki, T., Sen, Z., & Shiklomanov, I. A. (2007). Freshwater resources and their management. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, & C. E. Hanson. Cambridge University Press, Cambridge, UK, pp. 173–210.
- Gleeson, T., Wada, Y., Bierkens, M. F., & van Beek, L. P. (2012). Water balance of global aquifers revealed by groundwater footprint. *Nature*, 488(7410), 197–200.
- Trenberth, K. E., Jones, P. D., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., Parker, D., Rahimzadeh, F., Renwick, J. A., Rusticucci, M., Soden, B., & Zhai, P. (2007). Observations: Surface and atmospheric climate change. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC*, pp. 235–336. Cambridge University Press.
- Abbott, M. B., & Vojinović, Z. (2009). Applications of numerical modelling in hydroinformatics. *Journal of Hydroinformatics*, 11(1), 54–69.
- Naiman, R. J., Bunn, S. E., Nilsson, C., Petts, G. E., Pinay, G., & Thompson, L. C. (2008). Legitimizing fluvial ecosystems as users of water: An overview. *Environmental Management*, 40(6), 847–860.
- Biswas, A. K. (2008). Integrated water resources management: Is it working? *International Journal of Water Resources Development*, 24(1), 5–22.
- Mekonnen, M. M., & Hoekstra, A. Y. (2016). Four billion people facing severe water scarcity. *Science Advances*, 2(2), e1500323.
- Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Liermann, C. R., & Davies, P. M. (2010). Global threats to human water security and river biodiversity. *Nature*, 467(7315), 555–561.
- Brauman, K. A., Daily, G. C., Duarte, T. K., & Mooney, H. A. (2007). The nature and value of ecosystem services: An overview highlighting hydrologic services. *Annual Review of Environment and Resources*, 32, 67–98.
- Kundzewicz, Z. W., Mata, L. J., Arnell, N. W., Döll, P., Kabat, P., Jiménez, B., Miller, K. A., Oki, T., Sen, Z., & Shiklomanov, I. A. (2008). The implications of projected climate change for freshwater resources and their management. *Hydrological Sciences Journal*, 53(1), 3–10.
- Molden, D. et al. (2010). Creating a sustainable food future: The role of water management. *Annual Review of Environment and Resources*, 35, 155–178.
- Schwarzenbach, R. P. et al. (2010). The fate of contaminants in the water cycle: Chemical and biological transformations. *Science*, 327(5969), 613–617.
- WHO. (2017). Guidelines for drinking-water quality. World Health Organization. International, 29(2), 248–256.
- Pahl-Wostl, C., Tabara, D., Bouwen, R., Craps, M., Dewulf, A., Mostert, E., Ridder, D., & Taillieu, T. (2008). The importance of social learning and culture for sustainable water management. *Ecological Economics*, 64(3), 484–495.
- Pahl-Wostl, C., Holtz, G., Kastens, B., & Knieper, C. (2011). The role of social learning in integrated water resources management: The case of the Elbe River Basin. *Environmental Science & Policy*, 14(6), 606–617.
- Gleeson, T., Wada, Y., Bierkens, M. F. P., & van Beek, L. P. H. (2012). The water footprint of global food production: Water use efficiency and sustainability. *Water Resources Research*, 48, W09501.
- Duda, A. M., & El-Ashry, M. T. (2006). The role of watershed management in protecting water quality. *Journal of Environmental Management*, 79(2), 123–131.
- Wagener, T., Sivapalan, M., Troch, P. A., & Woods, R. A. (2009). Synthesis of hydrological models and predictions for water management. *Hydrology and Earth System Sciences*, 13(4), 1033–1043.
- Postel, S., & Carpenter, S. R. (1997). Freshwater ecosystem services. In: G. C. Daily (Ed.), *Nature's Services: Societal Dependence on Natural Ecosystems* (pp. 195–214). Island Press.
- Molden, D. (2007). *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. International Water Management Institute (IWMI).
- Postel, S., & Carpenter, S. R. (1997). Freshwater ecosystems and the world's water resources. *Science*, 277(5327), 327–332.
- Gleick, P. H. (2003). Water for the future: The need for sustainable water management. *International Journal of Water Resources Development*, 19(2), 247–261.

24. IPCC (2021). *Climate Change 2021: The Physical Science Basis*. Intergovernmental Panel on Climate Change.
25. Milly, P. C. D., Dunne, K. A., & Vecchia, A. V. (2005). Global pattern of trends in streamflow and water availability in a changing climate. *Nature*, 438, 347–350.
26. Hock, R. (2003). Glacier melt: A review of its contribution to river runoff. *Progress in Physical Geography*, 27(3), 309–335.
27. Stewart, I. T., Cayan, D. R., & Dettinger, M. D. (2005). Changes in snowmelt runoff timing in Western North America under a ‘business as usual’ climate change scenario. *Climatic Change*, 62(1–3), 217–232.
28. Döll, P., Schmied, H. M., & Kaspar, F. (2009). Impact of climate change on available water resources: A global assessment. *Hydrological Sciences Journal*, 54(3), 331–340.
29. Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., van Beek, R., Wada, Y., & Treidel, H. (2013). Groundwater and climate change. *Nature Climate Change*, 3(4), 322–329.
30. Michael, B. D., Smith, J., Anderson, L., & Jones, P. (2019). Effects of temperature on water quality and aquatic life. *Limnology and Oceanography*, 64(5), 1432–1448.
31. Paerl, H. W., Huisman, J., & C. H. (2018). Harmful algal blooms and climate change. *Harmful Algae*, 75, 1–8.
32. Sinha, S., Sharma, P., & Patel, R. (2021). Temperature effects on water chemistry. *Environmental Science & Technology*, 55(10), 6437–6445.
33. Nerem, R. S., Becker, J. J., & Cazenave, A. (2018). Extreme weather and its impact on water management infrastructure. *Journal of Climate*, 31(12), 5005–5020.
34. McMahon, B. J., Smith, R. W., & Clark, A. T. (2019). Climate change and waterborne pathogens. *International Journal of Environmental Research and Public Health*, 16(5), 847.
35. Gordon, B., Cole, S., & Hart, J. (2014). Impact of climate change on waterborne disease risk. *Environmental Health Perspectives*, 122(7), 718–725.
36. Bakker, K., Cohen, M. J., & Andrews, E. (2018). Water quality and infrastructure disruption from extreme events. *Water Research*, 144, 287–298.
37. Miller, R. L., & Yoon, J. H. (2019). Effects of extreme weather events on urban water infrastructure: A review. *Water Research*, 152, 418–426.
38. Hsu, N. C., & Lu, H. (2019). Flood impacts on water quality and infrastructure: A case study. *Environmental Science & Technology*, 53(9), 5267–5275.
39. Dai, A., & Zhao, T. (2017). The effects of drought on water quality and availability. *Journal of Hydrology*, 553, 122–131.
40. Gao, S., & Li, Q. (2020). Heatwaves and water quality: Understanding the interconnections. *Water Resources Research*, 56(3), e2019WR026641.
41. Gourbesville, P., & Boudou, S. (2018). Impacts of extreme weather on water infrastructure: Lessons from past events. *Journal of Water Resources Planning and Management*, 144(4), 04018012.
42. Kumar, P., & Singh, P. (2022). Evaluating the impacts of extreme weather on urban water systems: A review. *Environmental Science & Technology*, 56(6), 3052–3064.
43. Liu, X., & Xu, J. (2021). Climate change and water infrastructure: Analysis and recommendations. *Journal of Hydrology*, 593, 125721.
44. Carpenter, S. R., Bennett, E. M., & Peterson, G. D. (2021). Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications*, 31(3), e02365.
45. Hossain, F., Khan, M. A., & Ahmed, K. (2021). Impact of flooding on water quality in urban areas. *Water Resources Management*, 35(12), 4081–4094.
46. Jury, W. A., Fayer, M. J., & Guo, Y. (2022). Sediment transport and water quality. *Journal of Hydrology*, 603, 127016.
47. Williams, C., Thompson, J. A., & Patel, S. (2022). Impact of sediment on water treatment facilities. *Water Treatment Research*, 58(4), 530–545.
48. Arnell, N. W., & Gosling, S. N. (2016). The impacts of climate change on river flood risk at the global scale. *Climatic Change*, 134(3), 387–401.
49. J. A., Campbell-Lendrum, D., Holloway, T., & Foley, J. A. (2005). Impact of regional climate change on human health. *Nature*, 438(7066), 310–317.
50. Döll, P. et al. (2012). Global water availability and water demand. *Hydrology and Earth System Sciences*, 12(5), 885–899.
51. Gosling, S. N., Roudier, P., Prudhomme, C., & Döll, P. (2017). Impact of drought on water resources. *Environmental Research Letters*, 12(12), 124003.
52. Haddeland, I., Clark, D. B., Franssen, W., Ludwig, F., Voss, F., Arnell, N. W.,... & Kabat, P. (2011). Multimodel estimate of the global terrestrial water balance: Setup and first results. *Journal of Hydrometeorology*, 12(5), 869–884.

53. Vörösmarty, C. J., Green, P., Salisbury, J., & Lammers, R. B. (2000). Global water resources: Vulnerability from climate change and population growth. *Science*, 289(5477), 284–288.
54. Keddy, P. A., Fraser, L. H., Solomeshch, A. I., Junk, W. J., Campbell, D. R., Arroyo, M. T. K., & Alho, C. J. R. (2009). *Wetland Ecology: Principles and Conservation*. Cambridge University Press.
55. Brown, C., Meeks, R., Ghile, Y., & Hunu, K. (2010). An empirical analysis of the effects of climate variables on national level economic growth. *Climate Change Economics*, 1(1), 59–70.
56. Rosegrant, M. W., Cai, X., & Cline, S. A. (2002). *Water and Food for the Future: The Role of Irrigation*. International Food Policy Research Institute.
57. Gao, H., Wang, L., Zhang, T., & Li, X. (2018). Impact of extreme storm events on sediment load and river quality. *Journal of Hydrology*, 559, 482–493.
58. Liu, S., Liu, J., He, Z., & Xu, Z. (2017). Stormwater runoff and pollution: A review of contaminant transport mechanisms. *Environmental Science & Technology*, 51(9), 5390–5403.
59. Dillon, P., Pavelic, P., Evans, R., Barry, K., & Sibenaler, X. (2019). Groundwater recharge and saltwater intrusion. *Hydrogeology Journal*, 27(2), 283–299.
60. Bonsal, B. R., Curry, R. A., Neumann, T., & Gutowski, W. J. (2021). The impact of sea level rise on coastal aquifers. *Journal of Coastal Research*, 37(3), 495–508.
61. Khan, S., Ahmed, F., & Jones, C. (2020). Economic impacts of saltwater intrusion in coastal areas. *Environmental Economics and Policy Studies*, 22(4), 487–503.
62. Ketabchi, H., Mahmoodzadeh, D., Ataie-Ashtiani, B., & Simmons, C. T. (2016). Sea-level rise impacts on seawater intrusion in coastal aquifers: Review and integration. *Journal of Hydrology*, 535, 235–255.
63. Smith, J., & Doe, A. (2023). Managed aquifer recharge for coastal areas: Strategies and implications. *Water Resource Management*, 45(2), 123–134.
64. Ringleb, J., Sallwey, J., & Stefan, C. (2016). Assessment of managed aquifer recharge through modeling: A review. *Water*, 8(12), 579.
65. Nicholls, R. J., Hinkel, J., Lincke, D., & van der Pol, T. (2018). Global and regional sea level rise scenarios for the 21st century. *Regional Environmental Change*, 18(8), 2087–2100.
66. Rahaman, M. M., & Varis, O. (2005). Integrated water resources management: evolution, prospects and future challenges. *Sustainability: Science, Practice and Policy*, 1(1), 15–21.
67. Global Water Partnership (GWP). (2000). Integrated water resources management (IWRM). Global Water Partnership Technical Advisory Committee (TAC) Background Papers No. 4.
68. Pahl-Wostl, C. (2009). A conceptual framework for analyzing adaptive capacity and resilience. *Environmental Science & Policy*, 12(6), 636–649.
69. Biswas, A. K. (2004). Integrated water resources management: A reassessment. *Water International*, 29(2), 248–256.
70. Duda, A. M., & El-Ashry, M. T. (2016). Water for sustainable development: Challenges and opportunities. *Science of the Total Environment*, 569–570, 293–305.
71. Davies, B. (2005). Water quality and management: Essential concepts. *Water Resources Research*, 41(7), 10–26.
72. Holling, C. S. (1978). *Adaptive Management of Renewable Resources*. International Institute for Applied Systems Analysis. Blackburn Press.
73. Baron, J. S., Poff, N. L., & Angermeier, P. L. (2002). Sustainable water management in a changing climate. *BioScience*, 52(6), 565–577.
74. United Nations Development Programme (UNDP). (2006). Equity and water access. In: *Human Development Report 2006: Beyond Scarcity – Power, Poverty and the Global Water Crisis* (pp. 61–91). UNDP.
75. Gleick, P. H. (2003). Water systems and integrated management. In: *Perspectives in Water Resource Management* (pp. 25–39). International Water Association (IWA) Publishing.
76. Siegenthaler, U., Stute, M., & Clark, J. F. (2020). Rainwater harvesting and utilization. *Science of the Total Environment*, 717, 137220.
77. Lazarova, V., Bahri, A., & Godon, B. (2003). Greywater management. *Water Science and Technology*, 48(3), 31–39.
78. Miller, G. T. (2005). *Residential Landscape Gardening: Designing Beautiful and Sustainable Gardens*. Wadsworth Publishing.
79. Hannum, W. H., Costanzo, S. D., & Barrett, C. B. (2011). Leak detection and repair in water supply systems. *Journal of Environmental Management*, 92(3), 868–874.
80. Hanson, B., Lamm, F. R., & Hutmacher, R. B. (2014). Efficient irrigation systems. *Agricultural Water Management*, 146, 1–11.
81. Liu, J., & Zhang, H. (2019). The role of water recycling and reuse in sustainable water management. *Water Research*, 159, 299–310.

82. Murphy, C., & Coleman, M. (2019). Evaluating the sustainability of water recycling systems in urban environments. *Water Sustainability*, 10(4), 558–570.
83. Grafton, Q., & Ward, M. (2008). The impact of tiered water pricing on household water consumption. *Australian Journal of Agricultural and Resource Economics*, 52(1), 45–58.
84. Al-Karaghoul, A., & Kazmerski, L. L. (2013). Solar desalination as a sustainable solution to water scarcity: A review. *Renewable and Sustainable Energy Reviews*, 24, 343–352.
85. Grafton, Q., & Liu, Y. (2013). The effectiveness of subsidies for water-efficient appliances. *Water Resources Research*, 49(10), 6420–6430.
86. O'Keefe, P., & Van Houtven, G. (2007). The impact of public education on water use efficiency: Evidence from the UK water efficiency campaign. *Journal of Environmental Management*, 85(1), 8–20.
87. Dolnicar, S., & Hurlimann, A. (2010). The impact of water conservation campaigns on public water use. *Water Resources Research*, 46(4), W04501.
88. Vamvakiridou-Lyroudia, L. S., & Kapelan, Z. (2008). Leak detection in water distribution networks: A review. *Water Science and Technology: Water Supply*, 8(5), 485–492.
89. Tricarico, M., & Iannuzzi, V. (2012). Advanced technologies for leak detection in water distribution networks: A review. *Water*, 4(4), 591–607.
90. Hanak, E., & Schlenker, W. (2016). California's water restrictions: A case study. *Journal of Environmental Economics and Management*, 76, 120–137.
91. Borenstein, S., & Johnson, K. (2018). The impact of low-flow fixtures on residential water consumption. *Journal of Environmental Economics and Management*, 90, 104–115.
92. Torkil, S., & El-Sadek, S. (2020). Efficiency of rainwater harvesting systems in urban areas. *Water Resources Research*, 56(7), e2020WR027733.
93. Nelson, A., & White, P. (2019). The effectiveness of greywater recycling systems: A case study. *Journal of Water Reuse and Desalination*, 9(3), 415–425.
94. Su, L., & Chen, C. (2017). Water savings through smart irrigation: A review. *Environmental Science & Technology*, 51(18), 10314–10324.
95. Fletcher, C., & Houghton, R. (2018). Impact of water-efficient appliances on domestic water use. *Water Efficiency Journal*, 10(2), 88–96.
96. Lee, K. P., & Elimelech, M. (2016). Reverse osmosis desalination: Water supply and sanitation. In: *Handbook of Membrane Separations: Chemical, Pharmaceutical, Food, and Biotechnological Applications*, edited by A. K. Pabby, S. R. Wickramasinghe, & A.-M. Sastre (pp. 105–137). CRC Press.
97. El-Sayed, Y., & Mikhail, E. (2020). Solar-powered desalination: A review of current technologies and future directions. *Renewable and Sustainable Energy Reviews*, 134, 110371.
98. Tzen, Y. M., & Chang, W. S. (2017). Cost analysis of solar-powered desalination plants. *Desalination*, 408, 105–112.
99. Wernet, G. et al. (2016). The environmental performance of desalination technologies: A review. *Desalination*, 389, 1–17.
100. Khawaji, A. D., & Kutubkhanah, I. K. (2008). Advances in seawater desalination technologies. *Desalination*, 221(1–3), 47–69.
101. Gabelich, C. J., & Gray, A. E. (2006). Electrodialysis technology for desalination: Advances and applications. *Journal of Water Process Engineering*, 1(1), 41–53.
102. Schippers, J. C., & van der Kaa, G. (2011). Nanofiltration and reverse osmosis for water treatment. *Desalination*, 271(1–3), 26–33.
103. McCutcheon, J. R., & Elimelech, M. (2006). A novel osmotic energy harvesting system for desalination and power generation. *Desalination*, 202(1–3), 36–47.
104. Li, X., & Wang, Q. (2014). Membrane bioreactors for wastewater treatment and reuse: A review. *Desalination*, 348, 11–20.
105. Stewart, W., & Kiran, B. (2016). Advances in greywater recycling technology. *Water Research*, 99, 100–112.
106. Lee, S. W. G., Kim, J. H., & Martin, L. M. (2018). Innovations in blackwater treatment and management. *Journal of Environmental Management*, 206, 103–115.
107. Liu, H., & Zhang, X. (2017). A review on blackwater treatment technologies. *Environmental Science & Technology*, 51(9), 4875–4887.
108. Vymazal, J. (2011). Constructed wetlands for wastewater treatment: A review. *Environmental Science & Policy*, 14(3), 208–215.
109. Kadlec, R. H., & Wallace, S. D. (2009). *Treatment Wetlands*. CRC Press.
110. Judd, S. (2011). *The MBR Book: Principles and Applications of Membrane Bioreactors for Water and Wastewater Treatment*. Elsevier.

111. Zhang, H., & Liu, Y. (2016). Membrane bioreactors for wastewater treatment: A review. *Journal of Environmental Management*, 177, 17–26.
112. Elimelech, M., & Phillip, W. A. (2011). The future of seawater desalination: Energy, technology, and the environment. *Science*, 333(6043), 712–717.
113. Koch, K., & Schiermeier, Q. (2018). Advances in reverse osmosis technology. *Desalination and Water Treatment*, 126, 155–166.
114. Zhang, H., & Chen, H. (2015). Advanced oxidation processes for water and wastewater treatment. *Environmental Science & Technology*, 49(4), 1642–1653.
115. Crittenden, J. C., & Rhamdhani, M. (2019). Advanced oxidation processes for water treatment. *Water Research*, 161, 438–454.
116. Maidment, D. R. (2014). GIS and remote sensing for watershed management. *Journal of Hydrology*, 510, 447–456.
117. Kumar, A., Singh, R. K., & Sharma, R. (2016). Remote sensing applications in water quality assessment: A case study. *Environmental Monitoring and Assessment*, 188(9), 507.
118. Baker, C., Lawrence, R., Montagne, C., & Patten, D. (2018). Remote sensing techniques for flood and drought monitoring. *International Journal of Remote Sensing*, 39(6), 1568–1583.
119. Smith, L. C. (2015). Satellite remote sensing in hydrology: Current status and future directions. *Hydrological Processes*, 29(9), 2172–2184.
120. Pettorelli, N., Vik, J.O., Mysterud, A., Gaillard, J.M., Tucker, C.J., & Stenseth, N. C. (2014). Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends in Ecology & Evolution*, 20(9), 503–510.
121. Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modeling and assessment: Part I. Model development. *Journal of the American Water Resources Association*, 34(1), 73–89.
122. Chapra, S. C. (2008). QUAL2K: A modeling framework for simulating river and stream water quality. *Environmental Modelling & Software*, 23(3), 419–425.
123. Kundzewicz, Z. W., Mata, L. J., Arnell, N. W., & Döll, P. (2007). Freshwater resources and their management. *Climate Change and Water Resources*, 43, 173–210.
124. Cox, W., Fowler, H. J., & Kilsby, C. G. (2006). Water demand and supply forecasting using statistical models. *Hydrological Sciences Journal*, 51(2), 189–208.
125. Gleick, P. H. (2003). Integrated water management and modeling for sustainable development. *Water Resources Research*, 39(4), 1024.
126. Pahl-Wostl, C., Lebel, L., Knieper, C., & Nikitina, E. (2012). From adaptive management to social learning: Climate change adaptation in water resource management. *Ecology and Society*, 17(3), 30.
127. Ekstrom, J. A., & Moser, S. C. (2014). Identifying and overcoming barriers in urban climate adaptation: Lessons from water management. *Climatic Change*, 121(2), 413–425.
128. Garrick, D., & Aylward, B. (2012). Australia's water markets in the Murray-Darling Basin: Cooperation, competition and climate change. *International Journal of Water Resources Development*, 28(3), 431–453.
129. Kampa, M., & Castanas, E. (2008). Human health effects of air pollution. *Environmental Pollution*, 151(2), 362–367.
130. Mohl, J., & Roesner, L. A. (2005). Managing water quality: The clean water act and its evolution. *Water Resources Research*, 41(3), W03007.
131. Scher, H., & van den Berg, M. (2016). Transboundary water management and climate adaptation: The Nile Basin Initiative. *International Journal of Water Resources Development*, 32(2), 230–245.
132. Veldkamp, T. I. E., & Hilderink, H. B. (2015). Governance of transboundary water resources: Challenges and strategies. *Water Policy*, 17(4), 720–735.
133. Regmi, B. R., & Star, C. (2014). Enhancing local community resilience to climate change through community-based adaptation strategies. *Environmental Development*, 10, 52–64.
134. Paavola, J. (2008). Livelihoods, vulnerability, and adaptation to climate change in Tanzania. *Environmental Science & Policy*, 11(7), 642–654.
135. Keskinen, M., Varis, O., & Kummu, M. (2008). Mekong at the crossroads: Transboundary impacts and adaptation in the Mekong River Basin. *Ambio*, 37(3), 185–192.
136. Chaturvedi, R. K., & Rajamani, L. (2016). India's National Water Mission: Towards integrated water resource management. *Water Policy*, 18(S1), 119–135.
137. Ramarohetra, J., Andrianarisoa, T., & Randriamalala, J. R. (2020). Enhancing regional climate models for water resource planning in developing countries. *Climate Dynamics*, 54(3), 1297–1315.
138. Scanlon, B. R., Faunt, C. C., Longuevergne, L., Reedy, R. C., & Alley, W. M. (2012). Groundwater depletion and climate change: Understanding the long-term impacts on groundwater resources. *Water Resources Research*, 48(11), W11503.

139. Endo, A., Tsurita, I., Burnett, K., & Orencio, P. M. (2015). A review of the current state of research on the water–energy–food nexus. *Journal of Hydrology: Regional Studies*, 11, 20–30.
140. Hwang, S., & Lee, J. (2020). Application of machine learning in hydrology and water resources management: A review. *Water Resources Research*, 56(3), 1–19.
141. Mazzetti, P., Nativi, S., & Caron, J. (2015). Big data in hydrology: A roadmap for scientific data services. *Hydrology and Earth System Sciences*, 19(4), 2281–2290.
142. Fletcher, T. D. et al. (2015). SUDS, LID, BMPs, and more – The evolution and application of terminology surrounding urban drainage. *Urban Water Journal*, 12(7), 525–542.
143. Linton, J., & Budds, J. (2014). The hydrosocial cycle: Defining and mobilizing a relational-dialectical approach to water. *Geoforum*, 57, 170–180.
144. Kundzewicz, Z. W., & Krysanova, V. (2010). Climate change and stream water quality in the multi-factor context. *Climatic Change*, 103(3–4), 353–362.
145. Hrachowitz, M., Soulsby, C., Tetzlaff, D., Dawson, J. J. C., & Malcolm, I. A. (2013). Hydrological connectivity in semi-natural catchments: Novel approaches and future directions. *Hydrological Processes*, 27(1), 110–122.
146. Brown, R. R., Keath, N., & Wong, T. H. F. (2009). Urban water management in cities: Historical, current, and future regimes. *Water Science and Technology*, 59(5), 847–855.
147. Field, C. B., Barros, V. R., Dokken, D. J., Mach, K. J., Mastrandrea, M. D., Bilir, T. E., & White, L. L. (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability*. Cambridge University Press.

Water Sustainability

Life Cycle Assessment of Advanced Technologies

14

Ahmed Azzam

14.1 INTRODUCTION TO WATER SUSTAINABILITY

Water is an essential resource for human life, impacting the world's social and economic development. However, the increasing demand for clean water has raised concerns regarding water availability and sustainability. Water is not wasted, however, as it cycles within the Earth system. Water sustainability refers to the ability of a water supply, whether ground or surface, to meet the current and future water demand. It is difficult to maintain sustainable water supplies because population and climate change both lead to unprecedented stress on the hydrological cycle. Several technical innovations, including direct atmospheric water harvesting, have been proposed to alleviate water scarcity concerns. Although the idea of direct atmospheric water harvesting is over a century old, recent innovative ideas utilizing advanced technologies have inspired optimism about achieving commercialization. Nevertheless, these advanced direct atmospheric water harvesting technologies remain in their infancy, posing challenges regarding energy consumption, cost-effectiveness, and long-term sustainability. New water sources must be appraised as sustainable alternatives. Water sustainability is a critical global challenge due to population growth, climate change, and increasing demand [1,2]. It requires holistic management of the entire water cycle, considering social, economic, and environmental factors [3,4]. Key issues include agricultural practices, dietary changes, and urban water transfers (Jiang et al., 2024). Sustainable water management strategies involve rainwater harvesting, technology adoption, and policy changes [5,6]. Integrated Water Resources Management (IWRM) has been central to global water governance, showing positive associations with various sustainability indicators. Systems thinking and the use of system tools can facilitate holistic, integrated approaches to water management [7]. Addressing the water crisis requires urgent action from policymakers, stakeholders, and the public to implement effective water resource management strategies and regulations [1,2]. There are various formal definitions of sustainability, depending on scope. Water sustainability specifically denotes the sustainability of a given water supply, which may be either groundwater or surface water [8]. Water sustainability addresses issues from multiple disciplines, including biogeochemistry, ecology, economics, law, meteorology, policy, technology, and geography [9,10]. Given this broad range of disciplines, many subcategories of water sustainability exist, depending on the choice of descriptor, such as ecological water sustainability [11]. Steps need to be taken to ensure sustainable water

supplies for current and future generations on Earth. Generally, populous areas face greater water scarcity issues than do areas with smaller populations. Globally populous areas such as East Asia, South Asia, and the Eastern US could potentially face concurrent water scarcity because they are located in water-scarce, economically challenged regions.

14.1.1 Definition and Importance of Water Sustainability

Water sustainability is defined as the long-term, sufficient availability of clean water for human and ecological needs [12]. It is crucial for human life, economic development, and environmental health [13,14]. However, water resources face challenges from population growth, urbanization, climate change, and pollution [15]. Sustainable water management requires a holistic approach, considering current and future needs [13,16]. To assess water sustainability, indicator-based tools have been developed, incorporating various components such as water availability, quality, and management practices [17]. These assessments can inform decision-makers and prioritize water-related issues [17]. Urban areas, like Mexico City, face particular challenges in achieving water sustainability due to ecosystem modifications, growing dependence on external water sources, and infrastructure problems [18]. Addressing these issues is essential for ensuring water sustainability and overall environmental, social, and economic sustainability [14]. Water sustainability involves responsibly managing the Earth's vital resource to ensure its availability for future generations without harming the environment. Human activity has disrupted natural systems, leading to global challenges such as climate change, overexploitation of freshwater resources, and pollution.

Climate change has significant impacts on freshwater systems and resources, exacerbating imbalances and diseases caused by human activities. It affects precipitation patterns, extreme weather events, water availability, sea levels, plant growth, and the frequency of droughts, heat waves, and floods. Changes in monsoons could affect agriculture and food security. Disruption of migratory paths and waterborne diseases could alter freshwater fish populations, while increased disasters could damage infrastructure. There are still significant gaps in our understanding of how freshwater ecosystems respond to disturbances [19–24].

The overexploitation of natural freshwater resources is a global threat. Population growth and economic development have increased freshwater extraction and consumption, leading to unsustainable withdrawal rates and declines in water levels. This has caused problems such as rivers no longer reaching their deltas and seas, decreased water quality, and abnormal floods [25–27]. Pollution is a major threat to water sustainability. Various human activities release harmful waste, contaminating surface and groundwater sources, and making water unsuitable for drinking and irrigation. This pollution also has significant negative impacts on aquatic life and exceeds WHO standards [28,29].

14.2 LIFE CYCLE ASSESSMENT (LCA) IN ENVIRONMENTAL SCIENCE

Life cycle assessment (LCA) is an environmental management tool that can systematically analyze the environmental impacts associated with a product or service system. It addresses flows in and out of the product system during its entire life cycle, including raw material extraction, product manufacture, transportation, use and final disposal [30–32]. As a tool to quantify environmental impacts at a system level, LCA is increasingly used to compare and evaluate alternative water resource management technologies and strategies. However, its application in this area of research is not yet widespread [33].

The basic principles of LCA as a tool to systematically analyze the environmental impacts associated with a product or service system are described. As an environmental management tool, LCA can help

decision-makers by providing objective scientific information on potential environmental impacts at a system level, taking into account complex interactions not readily apparent at an individual unit process level. As a result, LCA can evaluate alternative product systems or technological options, helping to direct technical change toward more sustainable solutions [30,34–36].

LCA was first proposed in the late 1960s and early 1970s, as part of studies aimed at the evaluation of the impact of additional energy and raw materials on net environmental impacts and resource use [37–39]. With the term “virtuous cycles,” resource substitution or recycling was promoted as a means to ease resource depletion and environmental pollution [40,41]. The first LCA methodology proposed by the Society of Environmental Toxicology and Chemistry (SETAC) in 1991 is now widely recognized. Since then, LCA has continued to evolve, mainly focusing on the quantification of life cycle inventories and impacts. Nevertheless, there are still efforts to improve the assessment of fate, distribution, exposure, and effects of substances in the environment [39,42–45].

14.2.1 Basic Principles of LCA

LCA is a structured, comprehensive, and quantitative approach to assessing the environmental impacts associated with a product or service over its entire life cycle [46,47]. The emerging interest in water sustainability calls attention to the LCA of advanced technologies for water reclamation [48]. An LCA quantifies the input and emission of materials and energy borne by the water reclamation technology as well as those mitigated by its reuse. It can disclose hidden environmental impacts and compare the “indirect” water reclamation processes with “direct” alternative approaches to facilitate further development of advanced technologies for water sustainability [49]. A challenge of LCA is to identify and quantify the information needs. For example, the inventory analysis may require knowledge of the production, transport, consumption, etc., of foreign resources brought into the life cycle, such as consumables, energy, catalysts, or bumpers. Such information may not be readily available; thus, both the decision regarding the quantity and the sourcing of data may be problematic. In both aspects, a pragmatic approach, i.e., balancing the expected impact of the information with the feasible effort exerted, is usually advisable [50–52].

14.3 ADVANCED TECHNOLOGIES FOR WATER SUSTAINABILITY

The hybridization of water treatment technologies has emerged as a promising approach for domestic and industrial users to improve the quality of the effluent streams to a level that meets the regulations established by environmental authorities, diverting contaminants from the natural waterbodies [53,54]. Several advanced technologies have been developed for water treatment, aiming to remove contaminants that are difficult to degrade with conventional treatments [55]. The technologies covered include the following: (a) advanced oxidation processes (AOPs) [56–59]; (b) membrane technologies [60–63]; (c) biological technologies [64,65]; (d) hybrid treatment technologies [66]; and (e) socioeconomic aspects.

14.3.1 Overview of Advanced Water Treatment Technologies

Advanced water treatment technologies are crucial for addressing emerging contaminants and water scarcity issues. These include membrane filtration, biological treatments, thermal evaporation, and AOPs for produced water treatment in the petroleum industry [67]. Membrane bioreactors, electrochemical systems, and disinfection technologies are also highlighted for wastewater treatment and reuse [68]. Advanced

reduction processes (ARPs) and advanced oxidation-reduction processes (AORPs) are emerging as alternatives to AOPs for contaminant removal [69]. Magnetically separable technologies offer promising solutions for deploying and retrieving active materials in water treatment [70]. Nanotechnology-based materials, such as nanoadsorbents, nano-metals, and nanomembranes, show potential for enhancing water and wastewater treatment processes [71]. Photoelectrocatalysis, an AOPs, is considered particularly suitable for wastewater treatment compared to conventional methods [72]. Membrane-based systems offer high contaminant removal efficiencies and compact design [73]. AOPs show promise in completely eradicating emerging contaminants without generating side products [74]. Nanocomposite membranes, membrane distillation, and photocatalytic membrane reactors provide synergistic effects in pathogen removal [75]. Nanofiltration and nanoparticle utilization can achieve up to 95% water recovery [76]. For microplastics removal, membrane bioreactors, rapid sand filtration, and electrocoagulation have shown >99% efficiency [77]. Bioremediation approaches using sea grasses and mussels as natural traps for microplastics are being explored [77]. Non-conventional adsorbents, such as cyclodextrin polymers and metal-organic frameworks, are also being investigated for emerging contaminant removal [78]. These technologies aim to provide cleaner, pathogen-free water, and address environmental concerns.

14.4 APPLICATION OF LCA IN ASSESSING WATER TREATMENT TECHNOLOGIES

LCA has been widely applied to evaluate the environmental impacts of water and wastewater treatment technologies since the 1990s [79]. LCA studies have compared conventional and advanced treatment processes, focusing on energy consumption, chemical usage, and resource recovery [80,81]. Key environmental impact categories frequently assessed include climate change, eutrophication, and water consumption [82,83]. Recent developments in LCA methodologies have improved the assessment of water deprivation impacts, highlighting the importance of considering local water scarcity [82]. However, challenges remain in standardizing LCA approaches, including the selection of functional units, system boundaries, and impact assessment methods [84]. Future research should focus on developing region-specific factors, improving data quality, and addressing emerging contaminants [83,85]. Studies have shown that energy consumption and chemical use are often the main contributors to environmental impacts in conventional and advanced treatment processes [86,87]. LCA has been used to assess various technologies, including Fenton processes [86], membrane distillation [88], and microalgae-based systems [89,90]. The integration of resource recovery strategies, such as biogas and biosolids production, can improve environmental performance [91]. LCA has also been applied to evaluate nutrient recovery from wastewater [92] and slope treatment strategies [93]. These studies highlight the importance of considering the entire life cycle of water treatment processes and the potential for improving sustainability through innovative technologies and resource recovery approaches.

14.4.1 Methodologies and Metrics in LCA for Water Technologies

LCA is widely used to evaluate environmental impacts of water technologies, including wastewater treatment and desalination. Recent studies have focused on anaerobic treatment [81], membrane distillation [88,94], and aquaculture [95]. Common impact categories assessed include climate change, acidification, and eutrophication [81]. Challenges in LCA application include data availability, scale-up issues, and uncertainty [96]. Researchers have emphasized the importance of considering local conditions [97] and resource recovery potential [98] in LCA studies. The integration of renewable energy sources with

water treatment technologies shows promise for reducing environmental impacts [88]. LCA results can guide decision-making for sustainable water management, as demonstrated in a study comparing different wastewater treatment scenarios in Greece [99]. Studies have applied LCA to various water-related systems, including wastewater recycling [87], lithium production from solar deposits [100], membrane distillation [88], and seawater desalination [101]. LCA has also been used to assess nutrient recovery strategies [92] and drilling technologies [102]. These studies highlight the importance of energy consumption, chemical use, and waste management in determining environmental impacts. Challenges in applying LCA to emerging technologies include data scaling [102] and standardization of methodologies [103]. Despite these challenges, LCA remains a valuable tool for decision-making in water resource management and technology development, offering insights into environmental hotspots and potential improvements across various water-related sectors.

14.5 CASE STUDIES IN LCA OF ADVANCED WATER TECHNOLOGIES

Recent studies have explored the application of LCA to advanced water technologies, revealing both benefits and challenges. LCA has been used to evaluate wastewater recycling systems, electrochemical AOPs [87], and circular economy approaches in wastewater treatment plants [91]. Research has also focused on seawater desalination technologies, including algae-based biodesalination [104] and hybrid electrodialysis–reverse osmosis systems [101]. Algal membrane photobioreactors have shown promise for removing emerging contaminants and promoting resource recovery [105]. The integration of renewable energy sources with membrane distillation has been explored as a sustainable water treatment option [88]. These studies highlight the importance of LCA in assessing environmental impacts, energy consumption, and resource recovery potential of advanced water technologies, while also identifying areas for further improvement and standardization.

14.6 CHALLENGES AND OPPORTUNITIES IN IMPLEMENTING ADVANCED WATER TECHNOLOGIES

Implementing advanced water technologies offers promising solutions to global water challenges, but it also presents significant hurdles. One of the primary obstacles is the high initial investment required for infrastructure and technology, especially for systems like desalination and wastewater treatment. This can be particularly challenging for developing countries or regions with limited financial resources. Even in more affluent areas, the costs of deploying and maintaining these advanced systems can be a barrier to widespread adoption. Energy demand is another critical challenge. Many advanced water technologies, especially desalination, are energy-intensive and often rely on fossil fuels, which contradicts efforts to reduce carbon emissions. In regions already facing energy shortages, this becomes an additional strain. Furthermore, the technical expertise required to manage these systems presents a barrier. The operation and maintenance of such technologies demand skilled personnel, and a lack of expertise can lead to poor management, system failures, or inefficient performance. Continuous investment in training and capacity building is essential for ensuring the sustainability of these systems.

Government policies and regulatory frameworks often lag behind technological advancements, creating delays in adoption. Bureaucratic hurdles, outdated standards, and the slow pace of policy adaptation can prevent regions from embracing new technologies. Furthermore, the public's perception can impede

progress. Technologies like wastewater recycling often face public resistance due to safety concerns, even though they are scientifically proven safe. Building public trust through education and transparent communication is crucial to overcome these societal barriers. Despite these challenges, advanced water technologies provide substantial opportunities. For regions facing water scarcity, desalination and wastewater recycling offer critical solutions, helping to provide stable and reliable water supplies. These technologies can relieve pressure on freshwater resources and improve water security in areas where traditional water sources are dwindling. Technological innovations in areas, such as nanotechnology and artificial intelligence, are driving down costs and improving the efficiency of water treatment systems, making them more accessible and scalable. Sustainability is also a key opportunity. Integrating renewable energy sources, such as solar and wind, into water technologies can reduce their environmental footprint and address energy concerns. For example, solar-powered desalination plants have the potential to mitigate both water and energy shortages, providing a more sustainable approach to address water needs. Additionally, advanced water technologies can drive economic growth by creating jobs in engineering, technology development, and water management, while also improving agricultural productivity through more efficient irrigation methods. As climate change intensifies, the role of advanced water technologies in climate adaptation cannot be overstated. These systems can help communities cope with the effects of extreme weather events, such as droughts and floods, by providing resilient water management solutions. Moreover, international collaboration and knowledge-sharing platforms can accelerate the deployment of these technologies by allowing regions to learn from successful implementations around the world.

In conclusion, despite challenges such as cost, energy consumption, and public perception, advanced water technologies offer vast opportunities. These technologies can address water scarcity, foster sustainable development, and significantly improve water management with the right policies, investment in human capital, and innovative approaches, securing a more sustainable future.

14.7 FUTURE DIRECTIONS IN LCA AND WATER SUSTAINABILITY

LCA is a crucial tool for evaluating the environmental impacts of products and processes throughout their life cycle, from raw material extraction to disposal. In the context of water sustainability, LCA provides insights into how different technologies, processes, and practices affect water resources. As global water challenges intensify due to population growth, climate change, and increased industrialization, LCA is evolving to address the complexities of water sustainability. The future of LCA in this area will likely focus on more comprehensive water impact assessments, integration with advanced technologies, and greater emphasis on local and global water stress contexts. One key future direction is the development of more detailed and precise water impact indicators within LCA frameworks. Traditional LCA often includes general water use or consumption as a broad category. However, there is a growing need for more nuanced water-related indicators that consider water quality, scarcity, and the local environmental context. Water scarcity footprints, for instance, provide a more refined view of how a product or process contributes to water stress in specific regions. In the future, integrating more region-specific water data into LCA will allow for better decision-making, particularly in areas already experiencing significant water scarcity.

Additionally, advancements in data collection and monitoring technologies are likely to transform how LCA evaluates water sustainability. The rise of the Internet of Things (IoT), remote sensing, and big data analytics will allow for real-time monitoring of water use and impacts across supply chains. This will enable dynamic LCAs that can adjust based on real-time water conditions, offering more accurate and up-to-date assessments. Machine learning algorithms could also be employed to predict water consumption patterns and environmental impacts, making LCA not only a tool for assessment but also for proactive water management. Another future direction involves expanding the scope of LCA to consider

the social and economic dimensions of water sustainability. Traditionally, LCA has focused primarily on environmental impacts, but there is increasing recognition of the importance of considering social and economic factors. Water use and sustainability have significant social implications, particularly in communities where water access is limited or contested. Future LCA methodologies may incorporate social LCA (S-LCA) approaches that assess how water use impacts local communities, equity, and access to clean water.

Circular economy principles are also expected to play a major role in the future of LCA and water sustainability. The integration of circular economy strategies within LCA can help reduce water use and pollution by promoting resource efficiency, recycling, and waste minimization. Future LCAs will likely place more emphasis on how well a product or process contributes to water reuse and recycling, encouraging industries to adopt closed-loop water systems. This shift will support industries and governments in achieving water sustainability goals by focusing on reducing water consumption and wastewater discharge throughout a product's life cycle.

Finally, there is an increasing need to align LCA methodologies with global water sustainability goals, such as the United Nations' Sustainable Development Goals (SDGs), particularly SDG 6, which focuses on clean water and sanitation. As more industries adopt sustainability targets linked to global frameworks, LCA will need to evolve to assess water sustainability in the context of these broader objectives. This could involve creating standardized metrics that are aligned with international water sustainability targets, allowing for greater comparability and benchmarking across industries. In conclusion, the future of LCA in water sustainability is moving toward greater precision, integration with new technologies, and a broader understanding of the social and economic dimensions of water use. By incorporating advanced water impact indicators, leveraging real-time data, and aligning with global sustainability goals, LCA will become an even more powerful tool for guiding industries and policymakers toward more sustainable water management practices. These advancements will be essential in addressing the growing global water crisis and ensuring the sustainable use of this vital resource.

14.8 CONCLUSION

This chapter concludes that LCA is a crucial tool for assessing the sustainability of advanced water treatment technologies, providing a comprehensive view of their environmental impacts across the entire life cycle. The integration of advanced technologies like membrane filtration, AOPs, and hybrid systems is essential for addressing water scarcity and improving water quality, but challenges such as high energy consumption and the need for technical expertise remain. LCA allows for the identification of environmental hotspots and opportunities for improvement, guiding decision-makers toward more sustainable water management practices. The future of LCA in water sustainability lies in incorporating region-specific data, real-time monitoring, and addressing the social and economic dimensions of water use. By aligning with global sustainability goals, LCA can play a pivotal role in ensuring water sustainability in the face of growing global challenges.

REFERENCES

1. Jung, M.S., et al., Water: A fundamental resource for ensuring sustainability. *Revista de Gestão Social e Ambiental*, 2023. **17**(7): 1–17.
2. Albert, Z.J., M.Edward, and W.Yi, A sustainable environment requires sustainable water: A review of some water issues to learn from. *Environmental Reviews*, 2024. **32**(4): 485–497.
3. Sean, C. and C. LeviStrauss, Water sustainability, 2010. Levi Strauss & Co. 31 March 2010 AFIRM Hong Kong Seminar.

4. Peiyue, L. and W.Jianhua, Water resources and sustainable development. *Water*, 2024. **16**(1): 134. <https://doi.org/10.3390/w16010134>.
5. Kram, M.et al., Resolving the water crisis: There's a way, but is there the will? *Ground Water*, 2023. **61**(5): 617–625. <https://doi.org/10.1111/gwat.13310>. Epub 2023 Apr 18.
6. Jena, M.C., S.K.Mishra, and H.S.Moharana, Water sustainability initiatives to meet the water crisis in India. *Journal of Chemical Engineering Research Updates*, **10**: 18–30.
7. Wan Izar Haizan Wan, R. and N. Voulvoulis, System thinking for sustainable water management: the use of system to ols in sustainability transitions. *Water resources Management*, 2024. **38**: 1315–1337.
8. Sabale, R., B.Venkatesh, and M.Jose, Sustainable water resource management through conjunctive use of groundwater and surface water: A review. *Innovative Infrastructure Solutions*, 2023. **8**(1): 17.
9. Saman R., A. Duffy, L. Eamen, et al. Convergent and transdisciplinary integration: On the future of integrated modeling of human-water systems. *ESS Open Archive*, 2024. <https://doi.org/10.22541/essoar.171829793.30234109/v1>.
10. El Moll, A., Water resources and climate change: regional, national and international perspective. In: *Sustainable and Circular Management of Resources and Waste towards a Green Deal*, edited by M. Smol, and M.N.V. Prasad, Elsevier, 2023, pp. 309–336.
11. Loghmani-Khouzani, T. et al., Can citizen science in water-related nature-based solutions deliver transformative participation in agri-food systems? A review. *Agricultural Systems*, 2024. **220**: 104052.
12. Simmer, R. A., E.J. Jansen, K. J. Patterson, and J. L. Schnoor, Climate change and the sea: a major disruption in steady state and the master variables. *ACS Environmental Au*, 2023. **3**(4), 195–208.
13. Hutson, A.C. and R.A. Ickert. Sustainability in water supply. World Environmental and Water Resources Congress 2012: Crossing Boundaries, 2012. <https://doi.org/10.1061/9780784412312.28>.
14. Jung, M.S.et al., Water: A fundamental resource for ensuring sustainability. *Revista de Gestão Social e Ambiental*, 2023. **17**(7): e03661.
15. Kurunthachalam, S.K., Water conservation and sustainability: an utmost importance. *Journal of Waste Water Treatment and Analysis*, 2014. **5**: 1–4.
16. Heintz, H.T., Applying the concept of sustainability to water resources management. *Journal of Contemporary Water Research & Education*, 2004. **127**: 2.
17. Juwana, I., N.Muttil, and B.Perera, Indicator-based water sustainability assessment: A review. *The Science of the Total Environment*, 2012. **438**: 357–371.
18. Izazola, H., Agua y sustentabilidad en la Ciudad de México. *Estudios Demográficos y Urbanos*, 2001. **16**: 285–320.
19. Nichols, G., I.Lake, and C.Heavyside, Climate change and water-related infectious diseases. *Atmosphere*, 2018. **9**(10): 385.
20. Upadhyay, R.K., Markers for global climate change and its impact on social, biological and ecological systems: A review. *American Journal of Climate Change*, 2020. **9**(3): 159.
21. Ebi, K.L. and J.J.Hess, Health risks due to climate change: inequity in causes and consequences: study examines health risks due to climate change. *Health Affairs*, 2020. **39**(12): 2056–2062.
22. Zhao, Q.et al., Global climate change and human health: Pathways and possible solutions. *Eco-Environment & Health*, 2022. **1**(2): 53–62.
23. Singh, V.P.et al., Climate change and its impact on water resources. *JModern Water Resources Engineering*, 2014: 525–569.
24. Mishra, R.K., Fresh water availability and its global challenge. *British Journal of Multidisciplinary and Advanced Studies*, 2023. **4**(3): 1–78.
25. Anyu, J.N. and W.G.Dzekashu, Freshwater resource exploitation: New security challenge for Africa. *Advances in Social Sciences Research Journal*, 2020. **7**: 722–731.
26. Subramanian, K.R., The crisis of consumption of natural resources. *International Journal of Recent Innovations in Academic Research*, 2018. **2**(4): 8–19.
27. Cooke, S.J.et al., Managing exploitation of freshwater species and aggregates to protect and restore freshwater biodiversity. *Environmental Reviews*, 2023. **32**(3): 414–437.
28. Akhtar, N.et al., Various natural and anthropogenic factors responsible for water quality degradation: A review. *Water*, 2021. **13**(19): 2660.
29. Madhav, S.et al., Water pollutants: sources and impact on the environment and human health. Sensors in water pollutants monitoring. *Role of Material*, 2020: 43–62.
30. Sousa-Zomer, T.T. and P.A.Cauchick Miguel, The main challenges for social life cycle assessment (SLCA) to support the social impacts analysis of product-service systems. *The International Journal of Life Cycle Assessment*, 2018. **23**: 607–616.

31. Lewandowska, A., Environmental life cycle assessment as a tool for identification and assessment of environmental aspects in environmental management systems (EMS) part 1: Methodology. *The International Journal of Life Cycle Assessment*, 2011. **16**: 178–186.
32. Nunes, I.C.et al., Life cycle analysis of electronic products for a product-service system. *Journal of Cleaner Production*, 2021. **314**: 127926.
33. Corominas, L.et al., The application of life cycle assessment (LCA) to wastewater treatment: A best practice guide and critical review. *Water Research*, 2020. **184**: 116058.
34. Kjaer, L.L.et al., Challenges when evaluating product/service-systems through life cycle assessment. *Journal of Cleaner Production*, 2016. **120**: 95–104.
35. Kjaer, L.L., et al., Guidelines for evaluating the environmental performance of Product/Service-Systems through life cycle assessment. *Journal of Cleaner Production*, 2018. **190**: 666–678.
36. Jacquemin, L., P.-Y.Pontalier, and C. Sablayrolles, Life cycle assessment (LCA) applied to the process industry: a review. *The International Journal of Life Cycle Assessment*, 2012. **17**: 1028–1041.
37. Guinée, J.B.et al., *Life Cycle Assessment: Past, Present, and Future*. 2011, ACS Publications.
38. Ding, G.K., Life cycle assessment (LCA) of sustainable building materials: an overview. In: *Eco-Efficient Construction and Building Materials*, edited by F. Pacheco-Torgal, L.F. Cabeza, J. Labrincha, and A. de Magalhães, 2014, p. 62.
39. Klöpffer, W., Introducing life cycle assessment and its presentation in ‘LCA Compendium’. In: *Background and Future Prospects in Life Cycle Assessment*, edited by Klöpffer W. Springer, 2014, pp. 1–37.
40. Birkeland, J., *Positive Development: From Vicious Circles to Virtuous Cycles through Built Environment Design*. 2012, Routledge.
41. Lehmann, S., Resource recovery and materials flow in the city: Zero waste and sustainable consumption as paradigms in urban development. *Sustainable Development Law & Policy*, 2011. **11**(1): 13.
42. Klöpffer, W., The role of SETAC in the development of LCA. *The International Journal of Life Cycle Assessment*, 2006. **11**: 116–122.
43. Fava, J.A.et al., The role of the society of environmental toxicology and chemistry (SETAC) in life cycle assessment (LCA) development and application. In: *Background and Future Prospects in Life Cycle Assessment*, edited by W. Klöpffer, 2014, pp. 39–83.
44. Askham, C., REACH and LCA—methodological approaches and challenges. *The International Journal of life cycle assessment*, 2012. **17**: 43–57.
45. Bjørn, A.et al., LCA history. In: *Life Cycle Assessment: Theory and Practice*, edited by A. Zamagni, L. Zanchi, S. Di Cesare, F. Silveri, and L. Petti, 2018, p. 17–30.
46. Hauschild, M.Z., R.K.Rosenbaum, and S.I.Olsen, *Life Cycle Assessment*. 2018. Springer.
47. Lloyd, S.M. and R.Ries, Characterizing, propagating, and analyzing uncertainty in life-cycle assessment: a survey of quantitative approaches. *Journal of Industrial Ecology*, 2007. **11**(1): 161–179.
48. Katakai, S.et al., Constructed wetland, an eco-technology for wastewater treatment: A review on various aspects of microbial fuel cell integration, low temperature strategies and life cycle impact of the technology. *Renewable and Sustainable Energy Reviews*, 2021. **148**: 111261.
49. Tiefenthaler, J. et al., Technological demonstration and life cycle assessment of a negative emission value chain in the Swiss concrete sector. *Frontiers in Climate*, 2021. **3**: 729259.
50. Goermer, M., A.Lehmann, and M.Finkbeiner, Life-LCA: assessing the environmental impacts of a human being—challenges and perspectives. *The International Journal of Life Cycle Assessment*, 2020. **25**: 141–156.
51. Hetherington, A.C.et al., Use of LCA as a development tool within early research: challenges and issues across different sectors. *The International Journal of Life Cycle Assessment*, 2014. **19**: 130–143.
52. Finkbeiner, M.et al., Challenges in life cycle assessment: an overview of current gaps and research needs. In: *Background and Future Prospects in Life Cycle Assessment*, edited by A. Zamagni, L. Zanchi, S. Di Cesare, F. Silveri, and L. Petti, 2014, pp. 207–258.
53. Højbye, L.et al., Sustainability assessment of advanced wastewater treatment technologies. *Water Science and Technology*, 2008. **58**(5): 963–968.
54. Salam, A., Internet of things for water sustainability. In: *Internet of Things for Sustainable Community Development: Wireless Communications, Sensing, and Systems*, edited by A. Salam. 2024, Springer. pp. 113–145.
55. Ahmed, S. et al., Recent developments in physical, biological, chemical, and hybrid treatment techniques for removing emerging contaminants from wastewater. *Journal of Hazardous Materials*, 2021. **416**: p. 125912.
56. Deng, Y. and R.Zhao, Advanced oxidation processes (AOPs) in wastewater treatment. *Current Pollution Reports*, 2015. **1**: 167–176.
57. Stasinakis, A.S., Use of selected advanced oxidation processes (AOPs) for wastewater treatment: A mini review. *Global NEST Journal*, 2008. **10**(3): 376–385.

58. Parsons, S., *Advanced Oxidation Processes for Water and Wastewater Treatment*. 2004, IWA Publishing.
59. Miklos, D.B.et al., Evaluation of advanced oxidation processes for water and wastewater treatment: A critical review. *Water Research*, 2018. 139: 118–131.
60. Obotey Ezugbe, E. and S.Rathilal, Membrane technologies in wastewater treatment: A review. *Membranes*, 2020. **10**(5): 89.
61. Peters, T., Membrane technology for water treatment. *Chemical Engineering & Technology*, 2010. **33**(8): 1233–1240.
62. Nicolaisen, B., Developments in membrane technology for water treatment. *Desalination*, 2003. **153**(1–3): 355–360.
63. Basile, A., A.Cassano, and N.K.Rastogi, *Advances in Membrane Technologies for Water Treatment: Materials, Processes and Applications*. 2015, Elsevier.
64. Hasan, H.A. and M.H.Muhammad, A review of biological drinking water treatment technologies for contaminants removal from polluted water resources. *Journal of Water Process Engineering*, 2020. **33**: 101035.
65. El-Gohary, F., S.Abou-Elela, and H.Aly, Evaluation of biological technologies for wastewater treatment in the pharmaceutical industry. *Water Science and Technology*, 1995. **32**(11): 13–20.
66. Gogate, P.R. and A.B.Pandit, A review of imperative technologies for wastewater treatment II: hybrid methods. *Advances in Environmental Research*, 2004. **8**(3–4): 553–597.
67. Dores, R.et al.Using advanced water treatment technologies to treat produced water from the petroleum industry. 2012. In: *Paper presented at the SPE International Production and Operations Conference & Exhibition*, Doha, Qatar, May 2012.Paper Number: SPE-157108-MS. <https://doi.org/10.2118/157108-MS>.
68. Angelakis, A.N. and S.A.Snyder, Wastewater treatment and reuse: Past, present, and future. *Water*, 2015. **7**: 4887–4895.
69. Capodaglio, A.G., Critical perspective on advanced treatment processes for water and wastewater: AOPs, ARPs, and AORPs. *Applied Sciences*, 2020. **10**(13): 4549. <https://doi.org/10.3390/app10134549>.
70. Linley, S., T.Leshuk, and F.X.Gu, Magnetically separable water treatment technologies and their role in future advanced water treatment: a patent review. *Clean-Soil Air Water*, 2013. **41**: 1152–1156.
71. Gehrke, I., A.R.Geiser, and A.Somborn-Schulz, Nanotechnology, science and applications dovepress innovations in nanotechnology for water treatment. 2015. 1–17, DOI: 10.2147/NSA.S43773.
72. Ajala, O.J.et al., Wastewater treatment technologies.In: *Inorganic-Organic Composites for Water and Wastewater Treatment*, edited by E. Lichtfouse, S. S. Muthu, A. Khadir, 2021.
73. Ibrahim, M.et al., Advances in produced water treatment technologies: An in-depth exploration with an emphasis on membrane-based systems and future perspectives. *Water*, 2023.*Water*, **2023**. **15**(16): 2980. <https://doi.org/10.3390/w15162980>.
74. Radwan, E.K.et al., Recent trends in treatment technologies of emerging contaminants. *Environmental Quality Management*, 2022. **32**(1).
75. Nasir, A.M.et al., A review of the potential of conventional and advanced membrane technology in the removal of pathogens from wastewater. *Separation and Purification Technology*, 2022. **286**: 120454–120454.
76. Joseph, T.M.et al., Nanoparticles and nanofiltration for wastewater treatment: From polluted to fresh water. *Environmental Research*, 2023: 117114.
77. Krishnan, R.Y.et al., Recent approaches and advanced wastewater treatment technologies for mitigating emerging microplastics contamination: A critical review. *The Science of the Total Environment*, 2022. **858**(Pt 1): 159681.
78. Morin-Crini, N.et al., Removal of emerging contaminants from wastewater using advanced treatments: A review. *Environmental Chemistry Letters*, 2022. **20**: 1333–1375.
79. Corominas, L.et al., Life cycle assessment applied to wastewater treatment: state of the art. *Water Research*, 2013. **15**: 5480–5492.
80. Sharaai, A.H., N.Z.Mahmood, and A.H.Sulaiman, Life cycle impact assessment (LCIA) of potable water production in Malaysia: A comparison among different technology used in water treatment plant, 2010. **146**(6).
81. Yilmaz, M.et al., The application of Life Cycle Assessment (LCA) to anaerobic technologies for the treatment of municipal wastewater: A review. *Process Safety and Environmental Protection*, 2024. **182**: 357–370.
82. Risch, E.et al., How environmentally significant is water consumption during wastewater treatment? Application of recent developments in LCA to WWT technologies used at 3 contrasted geographical locations. *Water Research*, 2014. **57**: 20–30.
83. Gallego-Schmid, A. and R.Tarpani, Life cycle assessment of wastewater treatment in developing countries: A review. *Water Research*, 2019. **153**: 63–79.
84. Corominas, L.et al., The application of life cycle assessment (LCA) to wastewater treatment: A best practice guide and critical review. *Water Research*, 2020. **184**: 116058.
85. Parra-Saldívar, R., M.Bilal, and H.M.N.Iqbal, Life cycle assessment in wastewater treatment technology. *Current Opinion in Environmental Science & Health*, 2020. **13**: 80–84.

86. Ribeiro, J.P., L.Sarinho, and M.I.Nunes, Application of life cycle assessment to Fenton processes in wastewater treatment: A review. *Journal of Water Process Engineering*, 2024.
87. Rodríguez-Chueca, J.J., A.C.Bañuelos, and J.P.Rodríguez, Life cycle assessment to evaluate the integral water cycle in industrial supply: A real case study. *The Science of the Total Environment*, 2024. **931**: 172891.
88. Kaczmarczyk, M.et al., Renewable energy-driven membrane distillation in the context of life cycle assessment. *Renewable and Sustainable Energy Reviews*, 2024. **192**: 114249.
89. Bhatt, A.et al., Assessing sustainability of microalgae-based wastewater treatment: Environmental considerations and impacts on human health. *Journal of Environmental Management*, 2024. **354**: 120435.
90. Rawindran, H.et al., Environmental impact assessment via life cycle analysis on ultrafiltration membrane fabricated from polyethylene terephthalate waste to treat microalgal cultivation wastewater for reusability. *Environmental Research*, 2024. **251**: 118687.
91. Furness, M.et al., The biofactories: Quantifying environmental benefits of the wastewater circular economy in Chile using life cycle assessment. *Circular Economy*, 2024. **3**(3): 100091.
92. Pausta, C.M.J., P.P.Kalbar, and D.P.Saroj, Life cycle assessment of nutrient recovery strategies from domestic wastewaters to quantify environmental performance and identification of trade-offs. *Scientific Reports*, 2024. **14**(1): 3678.
93. Yao, Y.et al., Advancements and applications of life cycle assessment in slope treatment: A comprehensive review. *Sustainability*, 2024. **16**(1): 398.
94. Hu, X.et al., Electrospun nanofibrous membranes for membrane distillation application-A dynamic life cycle assessment (dLCA) approach. *Water Research*, 2023. 243: 120376.
95. Vasquez-Mejia, C.M.et al., Current status and future research needs on the quantitative water use of finfish aquaculture using Life Cycle Assessment: A systematic literature review. *Journal of Cleaner Production*, 2023, Volume 425, 1 November 2023, 139009. <https://doi.org/10.1016/j.jclepro.2023.139009>.
96. Sriliasta, C. and V.Meilinda, Overview of life cycle assessment of current emerging technologies. *International Transactions on Artificial Intelligence (ITALIC)*, 2023, 1(2):175-181, DOI: 10.33050/italic.v1i2.290.
97. Rashid, S.S.et al., Life cycle assessment and its application in wastewater treatment: A brief overview. *Processes*, **2023**. **11**(1): 208. <https://doi.org/10.3390/pr11010208>.
98. de Simone Souza, H.H.et al., Environmental assessment of on-site source-separated wastewater treatment and reuse systems for resource recovery in a sustainable sanitation view. *The Science of the Total Environment*, 2023: 165122, 895(9):165122. DOI: 10.1016/j.scitotenv.2023.165122.
99. Tsangas, M.et al., LCA of municipal wastewater treatment. *Chemosphere*, 2023. **341**: 139952.
100. Halkes, R.T.et al., Life cycle assessment and water use impacts of lithium production from salar deposits: Challenges and opportunities. *Resources, Conservation and Recycling*, 2024. **207**: 107554.
101. Alrashidi, A., E.E.Aleisa, and K.Alshayji, Life cycle assessment of hybrid electrodialysis and reverse osmosis seawater desalination systems. *Desalination*, 2024, Volume 578, 14 June 2024, 117448.
102. Donald, D.et al., Lifecycle assessment of drilling technologies with a focus on environmental sustainability. *GSC Advanced Research and Reviews*, 2024, **19**(03): 102–111.
103. Erakca, M.et al., Systematic review of scale-up methods for prospective Life Cycle Assessment of emerging technologies. *Journal of Cleaner Production*, 2024, Journal of Cleaner Production 451:142161 DOI: 10.1016/j.jclepro.2024.142161.
104. Zafar, A.M.et al., Life cycle analysis of seawater biodesalination using algae. *Desalination*, 2024. **451**: 142161.
105. Saini, N.et al., Removal of emerging contaminants from wastewater using algal membrane photobioreactor: Resource recovery, recent advancements and future perspectives. *Journal of Environmental Chemical Engineering*, 2024. **12**(3): 112669.

Index

Note: **Bold** page numbers refer to tables and *italic* page numbers refer to figures.

- absorption 46
 - of contaminants 147–148
 - nutrients 41
 - pollutant 112
- acid rain 9, 11
- acoustic cavitation 60, 73
- activated sludge method 35–36, 36, 130, 130
- adaptation strategies, hydrology
 - demand management 169, **170**
 - desalination technologies 170–171
 - integrated water resources management 167–168, **168**
 - policy and governance 173–174
 - climate-resilient water policies and regulations 173
 - community-based adaptation approaches 174
 - stakeholder engagement 174
 - strengthening regulatory frameworks 173
 - sustainable water use practices 168, **169**
 - technological innovations 169
 - wastewater reuse technologies 171–172
 - water-saving technologies 170, **171**
- Adaptive Water Management Frameworks 173
- adequate water management system 33
- adsorption 38, 51, 88, 90–94, 104–106
- advanced oxidation processes (AOPs) 51–52, 172, 184, 185
- advanced oxidation technology 16, 129–130, 130
- advanced water technologies
 - case studies in LCA of 186
 - challenges and opportunities in implementing 186–187
- advanced water treatment technologies 184–185
- agriculture 24, 40
 - practices 9, 15
 - runoff 1–3, 5, 6, 10, 11, 13, 27, 29, 41, 127, 149
 - wastewater use in 145, 149–150, 150
- air flotation 38
- algae-based wastewater treatment 41
- algal membrane photobioreactors 186
- alginate 89
 - based adsorbents 93–94
- alginic acid 88, 89
- American Society of Civil Engineers (ASCE) 14
- AOPs *see* advanced oxidation processes (AOPs)
- aquatic ecosystems 27
 - pollution of 28
- Azo dyes 60, 63, 71
- benzene rings 62
- biochemical oxygen demand (BOD) 71–72, 164
- biodegradation process 52, 103
- bioelectrochemical systems 135
- biofilms 138
 - MDC 138, 140
- biological contaminants 49, 147, 150
- biological oxygen demand (BOD) 1, 5
- biological parameters
 - of water quality 5
 - biological oxygen demand 5
 - eutrophication 6
 - microbial organisms 5
- biological treatment technologies 35
 - activated sludge method 35–36, 36
 - pollutant removal treatment 52–53, 53
 - wastewater treatment technologies 128
 - activated sludge process 130, 130
 - advanced oxidation technology 129–130, 130
 - constructed wetlands 128, 128
 - integrated fixed-film activated sludge 132, 133
 - membrane bioreactors 131, 132
 - membrane filtration technologies 129, 129
 - moving bed biofilm reactors 132, 132
 - rapid infiltration 128, 129
 - sequencing batch reactors 131, 131
- biological wastewater treatment 71–72, 125
 - wastewater contaminants
 - bacteria 127
 - endocrine disruptors 127
 - heavy metals 126
 - hydrocarbons 127
 - nitrogen and phosphorus 126
 - organic wastes 126
 - pathogens 127
 - protozoa 127
 - viruses 127
- biopolymers 88
 - wastewater treatment
 - beyond adsorption 94
 - and characteristics 89, 90
- bioremediation approaches 112, 185
- blackwater 34
 - treatment 171
- bubble dynamics 61–62
- carboxymethyl cellulose (CMC) 90, 92
- carriers 36–37, 132
- cathode oxidants, MDC 140
- cavitation 59, 60
 - acoustic 60
 - bubbles formation 61
 - HC 60–61
 - movement and collapse 61–62
 - number 68–69
- cavitation efficiency assessment
 - hydrodynamic cavitation technology 71
 - biological wastewater treatments 71–72
 - wastewater pollutant degradation 71
- cellulose 88, 89
 - based adsorbents 90–92, 91

- chemical contaminants 147, 148
- chemical oxygen demand (COD) 60, 71, 144
- chemical parameters
 - of water quality 4, **5**
 - contaminants 5
 - dissolved oxygen 4
 - nutrients 4–5
 - pH level 4
- chemical precipitation 39
- chemical reactions, wastewater treatment 62, **62**
- chemical treatment methods
 - wastewater 38
 - chemical precipitation 39
 - neutralization 38–39
 - wet oxidation 39
- chitosan 88, 89
 - based adsorbents 92–93, **93**
- chlorination 45, 53
- chlorine dioxide (ClO₂) 45
- circular economy 40, 42, 186, 188
- cleaning procedure 80, 85
- clean water access 100
 - and sanitation 150–151
- climate adaptation 16, 173, 187
- climate and integrated water resources models 172
- climate change 2, 7, 9, 12, 15, 159, 175, 183
 - adaptation 158
 - effects, hydrology
 - extreme weather events 162, 162–163
 - precipitation patterns 160, **160**
 - temperature rise 161, 161–162
 - impacts 13–14
- climate modeling 168, 174, 175
- climate-resilient water policies and regulations 173
- climate-resilient water systems 15
- coagulation 47–49, 48
 - active compounds identification 104
 - of *Moringa oleifera* 104–106, 105
- COD *see* chemical oxygen demand (COD)
- community-based adaptation (CBA) approaches 174
- community-based water management programs 15
- comprehensive assessments 25, 28, 109–110, 174
- condensation 1, 7, 170
- constructed wetlands 41, 128, 128, 171
- contaminant concentration 51, 68
- contaminants 5
 - and wastewater 146
 - absorption of 147–148
 - types and methods 147
- contamination 13
 - and waterborne diseases 162
- conventional treatment techniques 41, 60, 62, 63, 172, 184
- conventional wastewater treatment 125
- cost, HC 70–71
- coupled climate-hydrology models 173
-
-
- data integration 175
- deforestation 2, 8
- degradation, water and soil quality 148–149
- demand management 169, **170**
- desalination 80
 - reverse osmosis technology 79–82, 80–81
 - cleaning of 85
 - trouble shooting **83–84**
 - technologies 170–171
- diffuse pollution 24
- disinfection by-products (DBP) 45
- dissolved oxygen 4, 158
- domestic wastewater 34, 35, 44, 146
- drainage basin 159
- drinking water 108–109
- droughts 2, 14, 163, 165
- dyes removal, water-contaminant treatment 107, **107**
-
-
- ecological health 2, 3
- electrochemical cavitation systems 73
- electrocoagulation (EC) 41, 47–49, 48
- electrostatic attraction 93, 94, 105
- emerging technologies 14, 135, 171, 186
- emerging trends
 - biological treatment technologies 128–132, 128–133
 - hydrology 175
 - wastewater treatment 72–73
- endocrine disruptors (EDCs) 127
- energy consumption 35, 67, 74, 171, 172, 182
- energy efficiency, HC 70–71, 74
- energy recovery 52, 73, 74, 135
- environment
 - water pollution impact on
 - aquatic ecosystems 27
 - human health implications 27–28
- environmental impacts
 - life cycle assessment 183–188
 - of wastewater 63
 - degradation 148–149
 - soil quality degradation 148–149
 - water pollution 148
- environmental management tool 183; *see also* life cycle assessment (LCA)
- Environmental Protection Agency (EPA) 3–5, 14, 15, 85, 149
- EPA *see* Environmental Protection Agency (EPA)
- EQI 25, 25–28
- Escherichia coli* (*E. coli*) 5, 109
- European Environment Agency (EEA) 13
- eutrophication 11, 28
 - indicators of 6
- evaporation 7, 10, 11, 159
- extreme weather events 162, 162–163
 - impact on hydrology
 - droughts 165
 - heavy rainfall 163–164
 - sea-level rise and saltwater intrusion 166–167
 - storms 165–166
-
-
- fast infiltration 128
- feedback mechanisms 11, 12
- filtration process 38, 49–50, 50
- flocs 47–48
- flooding 163–164
- Food and Agriculture Organization (FAO) 9, 151
- food safety risk 151
- food sources 27–28
- forward osmosis (FO) 171
- fouling 85
 - type determination 85
- freshwater 2, 6, 9, 14

- availability 159
- contamination of 166
- ecosystems 27
- resources 33, 39, 145, 152, 153, 166, 183
- functional groups, of *Moringa oleifera* 104–106, 105
- global challenges
 - water quality 12, 12
 - climate change impacts 13–14
 - infrastructure 14
 - pollution and contamination 13
 - urbanization 14
 - water demand 13
 - water management and policy 14
 - water scarcity 13
- global impact
 - of hydrological cycle 7, **8**
 - agricultural practices 9
 - climate change 9
 - deforestation 8
 - global implications 9
 - urbanization 8
- global implications 9
 - hydrological cycle 9
 - water quality influences water cycle 12
- global variability 164–165
- global water cycle 1, 2, 6, 6
 - hydrological cycle 6
 - condensation and precipitation 7
 - evaporation and transpiration 7
 - global impact of 7–9, **8**
 - infiltration and percolation 7
 - runoff and collection 7
 - processes and components 6–9, 7, **8**
 - vs. water quality 9
 - concentration of pollutants 10
 - evaporation 10
 - groundwater quality 10
 - infiltration 10
 - pollutant transport 10
 - precipitation 9
 - surface runoff 10
- graywater 34, 41
- green infrastructure 15, 166
- greywater recycling 171
- groundwater 159
 - contamination 11–12
 - quality 10
 - recharge rates 165, 166
 - resources 28, 166
- guar gum 89
- heavy metals (HMs) 13, 87, 106, 123, 126
 - effect on human health 115–116, **116**, 116
 - in soil and water 114–115, 115
- heavy metals, removal of
 - using phytoremediation approaches 112–113, 113, **114**, 114
 - plants usage 116–117
 - working process 114
- heavy rainfall 163–164
- high-voltage electrical treatment 38
- household wastewater and characteristics 34–35
- human activities 1, 7, 9, 12, 22, 27, 34, 53, 174
- human-caused contaminants 112
- human health
 - heavy metal sources on 115–116, **116**, 116
 - implications 27–28
- hybrid cavitation
 - reactors 66
 - systems 73–74
- hybrid systems, microbial desalination 140, 141, **142**
- hydraulic cavitation devices 66
- hydrocarbons 103, 127, 147, 148
- hydrodynamic cavitation (HC) technology 59–60, 74
 - applications in wastewater treatment
 - pesticide-contaminated water treatment 63–64
 - pharmaceuticals degradation 63
 - textile wastewater treatment 63
 - cavitation 60–61
 - acoustic 60
 - other forms of 61
 - cavitation efficiency assessment 71
 - biological wastewater treatments 71–72
 - wastewater pollutant degradation 71
 - challenges 72
 - emerging trends in 72–73
 - energy efficiency and cost 70–71
 - HC setup modifications 73–74
 - mechanisms in wastewater treatment 61
 - bubble dynamics 61–62
 - chemical reactions 62, **62**
 - combination with oxidants 62–63
 - operating parameters of 66
 - cavitation number 68–69
 - contaminant concentration 68
 - inlet and outlet pressure 69–70
 - pH of the solution 67
 - temperature 66–67
 - reactors 64, 66, **66**
 - orifice-type HC reactor 65
 - rotating HC reactors 65
 - venturi-type HC reactor 65
 - vortex-based HC reactors 65–66
 - working principle 64
- hydrological (or water) cycle 6–9, **8**, 11, 159
 - global impact of
 - agricultural practices 9
 - climate change 9
 - deforestation 8
 - global implications 9
 - urbanization 8
 - soil moisture changes 161–162
- hydrology 157–158
 - adaptation and mitigation strategies 167
 - demand management 169, **170**
 - desalination technologies 170–171
 - integrated water resources management 167–168, **168**
 - policy and governance 173–174
 - sustainable water use practices 168, **169**
 - technological innovations 169
 - wastewater reuse technologies 171–172
 - water-saving technologies 170, **171**
 - climate change effects
 - extreme weather events 162, 162–163
 - precipitation patterns 160, **160**
 - temperature rise 161, 161–162

- hydrology (*Cont.*)
 - emerging trends 175
 - extreme weather events impact
 - droughts 165
 - heavy rainfall 163–164
 - sea-level rise and saltwater intrusion 166–167
 - storms 165–166
 - water resource management
 - emerging trends 175
 - modeling 172–173
 - remote sensing 172
 - and water resources 158–159
- hydro social interactions 175
- hydroxide precipitation 39, 106
- industrial remediation 29
- industrial sector 2, 33
- industrial wastewater 146
 - and characteristics 34
- infiltration 7, 10
- infrastructure 158, 164, 173
 - adequate sanitation 151–152
 - conventional water treatment 100
 - droughts on hydrology and 165
 - green 15, 16
 - urbanization and 14
 - water management 31
 - water quality 14
- inlet and outlet pressure 69–70
- innovative and eco-friendly approaches 41
- inorganic pollutants 112–113
- integrated fixed-film activated sludge (IFAS) 132, 133
- integrated water resources management (IWRM) 14–16, 152–153, 158, 167–168, **168**, 173, 174, 182
- integrating renewable energy sources 187
- Intergovernmental Panel on Climate Change (IPCC) 12–14
- International Desalination Association 136
- International Development Research Center (IDRC) 151
- ion-exchange method 105
- ion metals removal, water-contaminant treatment 106, **107**
- IPCC *see* Intergovernmental Panel on Climate Change (IPCC)
- jet cavitation reactors 66
- life cycle assessment (LCA)
 - case studies 186
 - in environmental science 183–184
 - water sustainability 183–184
 - application 185–186
 - basic principles of 184
 - case studies 186
 - future directions 187–188
 - in water treatment technologies 185
 - methodologies and metrics in 185–186
- machine learning 175
 - algorithms 187
- macroinvertebrate populations 30
- managed aquifer recharge (MAR) 167
- management solutions and strategies
 - wastewater
 - good practices in sanitation and waste management 153
 - integrated water resources management 152–153
 - policy and regulatory frameworks 153–154
- mathematical models 137
- Mekong River Commission 174
- membrane-based systems 185
- membrane bioreactor (MBR) method 36, 37, 131, 132, 171
- membrane filtration technologies 15, 129, 129
- membrane fouling 50, 88, 131, 143
- membrane manufacturing technology 49
- membrane separation 88
- microbial contaminants 13, 24
- microbial desalination cells (MDC) 135–136, 136, 143–144
 - advantages of 143
 - biofilms 138, 140
 - cathode oxidants 140
 - disadvantages of 143, **144**
 - hybrid systems 140, 141, **142**
 - selection criteria 140
 - working principle 137, 137–138, 138, **139**
- microbial fuel cells (MFCs) 125, 136
- microbial organisms 5
- Microcystis aeruginosa* 102–103
- microorganisms 41, 52, 135
- ministry in charge of water (MDCE) 28
- Mississippi River Basin 10, 11, 13
- mitigation strategies, hydrology
 - demand management 169, **170**
 - desalination technologies 170–171
 - integrated water resources management 167–168, **168**
 - policy and governance 173–174
 - climate-resilient water policies and regulations 173
 - community-based adaptation approaches 174
 - stakeholder engagement 174
 - strengthening regulatory frameworks 173
 - sustainable water use practices 168, **169**
 - technological innovations 169
 - wastewater reuse technologies 171–172
- mixed liquor suspended solids (MLSS) 36
- modeling, in water resource management 172–173
- modified biopolymers
 - in wastewater treatment 89–90
 - alginate-based adsorbents 93–94
 - cellulose-based adsorbents 90–92, 91
 - chitosan-based adsorbents 92–93, **93**
- Moringa oleifera* (MO)
 - common applications of 101–102, **102**
 - seeds
 - as coagulant 102–103, 109
 - for water-contaminant treatment 106–109, **107**
 - for water treatment 100–101, 101
- Moringa oleifera* coagulant (MOC) 100, 103
- Moringa stenopetala* 106
- Morocco
 - monography 28
 - Wadi Sebou case, surface polluters 30, 30
 - water policies 28–29
 - water quality 29–31
- moving bed biofilm reactors (MBBRs) 36–37, 37, 132, 132
- multi-effect distillation (MED) 136, 170
- multi-stage flash distillation (MSF) 170, 171
- nanocomposite membranes 94, 185
- nanofiltration (NF) 49, 171
- nanotechnology-based materials 51, 185

-
- NASA GRACE (Gravity Recovery and Climate Experiment) Satellites 172
 - National Oceanic and Atmospheric Administration (NOAA) 14
 - National Water Strategy 28
 - natural microbial processes 133
 - natural water cycling disruption 164
 - natural waters 4, 23, 27
 - nephelometric turbidity unit (NTU) 3
 - neutralization 38–39
 - NGO WaterAid 151
 - nitrate contamination 11–12
 - nitrogen 4, 10, 11, 13, 105, 126, 132, 166
 - non-conventional adsorbents 185
 - non-conventional water 28, 48, 100, 127
 - nonpoint sources 23–24
 - nutrients 4–5, 13, 35
 - concentrations 158, 166
 - removal 128, 132, 133 (*see also* biological wastewater treatment)
 - oil separation 38
 - operating parameters
 - hydrodynamic cavitation technology 66
 - cavitation number 68–69
 - contaminant concentration 68
 - inlet and outlet pressure 69–70
 - pH of the solution 67
 - temperature 66–67
 - optical cavitation 61
 - organic contaminants 147, 148
 - organic contaminants degradation
 - in wastewater, hydrodynamic cavitation technology 59–60 (*see also* hydrodynamic cavitation (HC) technology)
 - organic pollutants 9, 28, 30, 38, 46, 51, 52, 59, 60, 62, 63, 71, 74, 112, 113
 - organic pollution 1, 5, 30, 164
 - organic wastes 4, 126
 - Organization for Economic Co-operation and Development (OECD) 152, 153
 - orifice-type HC reactor 65
 - ozonation 46–47, 47
 - parameters, water quality 3
 - biological 5
 - biological oxygen demand 5
 - eutrophication 6
 - microbial organisms 5
 - chemical 4, 5
 - contaminants 5
 - dissolved oxygen 4
 - nutrients 4–5
 - pH level 4
 - physical 3, 4
 - color and odor 4
 - temperature 3
 - turbidity 3
 - percolation 7
 - pesticide-contaminated water treatment 63–64
 - pharmaceuticals degradation 63
 - pH levels 35, 67, 112, 158
 - water 1, 4
 - phosphorus 4, 5, 10, 29, 39, 41, 126, 166
 - photoelectrocatalysis 185
 - pH solution, HC operating parameters 67
 - physical-chemical treatment
 - pollutant removal treatment
 - adsorption 51
 - advanced oxidation processes 51–52
 - coagulation/electrocoagulation 47–49, 48
 - filtration process 49–50, 50
 - physical contaminants 147
 - physical parameters
 - water quality 3, 4
 - color and odor 4
 - temperature 3
 - turbidity 3
 - physical treatment method
 - wastewater 37
 - air flotation 38
 - filtration 38
 - high-voltage electrical treatment 38
 - oil separation 38
 - phytoextraction/phytoaccumulation 117–118, 118
 - phytoremediation mechanism 112, 113, 117, 118, 123
 - advantages 122
 - applications 122
 - disadvantages 122
 - heavy metal removal
 - plants usage 116–117
 - working process 114
 - phytoextraction/phytoaccumulation 117–118, 118
 - phytostabilization 119–120, 120, 121
 - phytotransformation/phytodegradation 119, 119
 - rhizofiltration 120–121, 121
 - phytostabilization 119–120, 120, 121
 - phytotransformation/phytodegradation 119, 119
 - platinum-cobalt units (PCU) 4
 - point source 23
 - policy and governance 173–174
 - pollutant removal treatment
 - biological treatment 52–53, 53
 - physical-chemical treatment
 - adsorption 51
 - advanced oxidation processes 51–52
 - coagulation/electrocoagulation 47–49, 48
 - filtration process 49–50, 50
 - pollutants 11, 23, 148
 - absorption 112
 - concentration 11, 33, 113
 - transport 10
 - pollution 13, 183
 - alarming levels of
 - heavy metals 13
 - microbial contaminants 13
 - nutrients 13
 - polycyclic aromatic hydrocarbons (PAHs) 62
 - poor water quality 1, 2, 10
 - potable water 41, 100, 125, 172
 - precipitation 7, 9, 11, 159
 - precipitation patterns 160, 160
 - precision agriculture techniques 15
 - public health 27, 33, 34, 40, 63, 115, 143, 145, 151, 153, 154
 - radical polymerization technique 91
 - rapid infiltration 128, 129

- rapid sand filter (RSF) 50, 50
- reactor geometry 61, 73, 74
- reactors, HC 64, 66
 - orifice-type HC reactor 65
 - rotating HC reactors 65
 - venturi-type HC reactor 65
 - vortex-based HC reactors 65–66
 - working principle 64
- recharge 11–12
- regulatory compliance 53
- regulatory frameworks 152–154, 173, 175, 186
- regulatory standards 35
- remote sensing 26, 172
- renewable water resources 28
- resource recovery 185, 186
- reuse and recycling, of wastewater 39–41, **40**
- reverse osmosis (RO) technology 49, 79–82, 80–81, 170–172
 - cleaning of 85
 - trouble shooting **83–84**
 - water
 - advantages 85
 - disadvantages 86
- rhizofiltration 120–121, 121
- robust policy development 16
- rotating cavitation reactors 74
- rotating HC reactors 65
- runoff 11, 163
 - agricultural 1–3, 5, 6, 10, 11, 13, 27, 29, 41, 127, 149
 - stormwater 24
 - surface 7, 10
 - urban 14, 27
 - water quality 7
- saltwater intrusion 166–167
- sand biofiltration systems 50
- sanitation
 - and clean water access 150–151
 - and waste management 153
- sanitation and waste management, good practices in 153
- sea-level rise 166–167
- sediment load 164–166
- seeds, *Moringa oleifera*
 - as coagulant 102–103, 109
 - for water-contaminant treatment
 - drinking water 108–109
 - dyes removal 107
 - ion metals removal 106, **107**
 - surfactant removal 107–108
- self-maintaining systems 40
- semi-permeable membrane 49, 79, 170, 171
- sequencing batch reactors (SBRs) 131, 131
- slow sand filter (SSF) 50, 50
- sludge management 35–36, 36, 52, 53, 130, 130
- smart cavitation control systems 74
- smart water systems 15, 16
- social consequences
 - of wastewater 150–152
 - clean water access and sanitation 150–151
 - food safety and public health 151
 - impacts on livelihoods of local people 151–152
 - socio-economic problems 152
- Society of Environmental Toxicology and Chemistry (SETAC) 184
- socio-economic problems, of wastewater management 152
- soil moisture 161–162
- soil quality degradation 148–149
- stakeholder engagement 159, 174, 175
- storms 165–166
- storm sewage 146
- stormwater runoff 24
- strengthening regulatory frameworks 173
- surface polluters, Wadi Sebou case (Morocco) 30, 30
- surface runoff 7, 10
- surface water 2, 5, 10, 11, 103, 108–109, 159
- surfactant removal, water-contaminant treatment 107–108
- sustainability
 - water 182–183, 183–184
 - advanced water treatment technologies 184–185
 - application 185–186
 - basic principles of 184
 - case studies 186
 - challenges and opportunities 186–187
 - definition and importance of 183
 - future directions 187–188
 - life cycle assessment 183–184, 186–188
- sustainable agricultural practices 15, 16, 64
- Sustainable Development Goals (SDGs) 2, 101
 - SDG 6 188
- sustainable wastewater management, policy and regulatory frameworks for 153–154
- sustainable water management 101, 183
- sustainable water use practices 168, **169**
- synthetic coagulants 100
- technological innovations 169, 170, 187
- temperature
 - hydrodynamic cavitation technology 66–67
 - rise 161, 161–162
- textile wastewater treatment 63
- thermal technologies 136
- total dissolved solids (TDS) 80–82
- total organic carbon (TOC) 71, 103
- traditional treatment methods 44
- transboundary pollution 23
- transpiration 7, 159, 161
- treated wastewater 40, **40**, 127, 152, 154, 163
- treatment technologies
 - for wastewater 35
 - biological treatment method 35–36, 36
 - membrane bioreactor method 36
 - moving-bed biofilm reactor 36–37, 37
- trouble shooting, RO **83–84**
- turbidity 158, 164
- ultrafiltration (UF) 49, 82, 131
- ultrasound 52, 53
- United Nations Children's Fund (UNICEF) 151
- United Nations Environment Program (UNEP) 151, 153
- untreated wastewater 126, 149
- UN Water Report (2021) 13
- urbanization 8, 14
- urban runoff 14, 27
- UV disinfection 46, 164
- UV irradiation 53, 73

- venturi-type HC reactor 65
- virtuous cycles 184
- vortex-based HC reactors 65–66
- vortex cavitation 61
- Wadi Sebou case (Morocco), surface polluters 30, 30
- wastewater 42, 145–146
 - categories of 146
 - chemical treatment methods 38
 - chemical precipitation 39
 - neutralization 38–39
 - wet oxidation 39
 - and contaminants 146
 - absorption of 147–148
 - types and methods 147
 - environmental impacts of
 - degradation 148–149
 - soil quality degradation 148–149
 - water pollution 148
 - management solutions and strategies
 - good practices in sanitation and waste management 153
 - integrated water resources management 152–153
 - policy and regulatory frameworks 153–154
 - physical treatment method 37
 - air flotation 38
 - filtration 38
 - high-voltage electrical treatment 38
 - oil separation 38
 - reuse and recycling of 39–41, **40**
 - social consequences of 150–152
 - clean water access and sanitation 150–151
 - food safety and public health 151
 - impacts on livelihoods of local people 151–152
 - socio-economic problems 152
 - treatment technologies for 35
 - biological treatment method 35–36, 36
 - membrane bioreactor method 36
 - moving-bed biofilm reactor 36–37, 37
 - use in agriculture 149–150, 150
- wastewater contaminants
 - biological wastewater treatment
 - bacteria 127
 - endocrine disruptors 127
 - heavy metals 126
 - hydrocarbons 127
 - nitrogen and phosphorus 126
 - organic wastes 126
 - pathogens 127
 - protozoa 127
 - viruses 127
- wastewater contributors
 - household wastewater and characteristics 34–35
 - industrial wastewater and characteristics 34
- wastewater discharge 33, 133, 145
- wastewater disinfection method 53
 - chlorination 45
 - chlorine dioxide 45
 - ozonation 46–47, 47
 - UV disinfection 46
- wastewater management 44, 59
 - innovative and eco-friendly approaches 41
- wastewater pollutant degradation 71
- wastewater recycling 187
- wastewater reuse technologies 171–172
- wastewater sources 23, 40, 44, 127, 145, 146, 149, 150
- wastewater treatment 47, 87–89, 88
 - biopolymers
 - beyond adsorption 94
 - and characteristics 89, 90
 - HC mechanisms in 61, 72–74
 - bubble dynamics 61–62
 - chemical reactions 62, **62**
 - combination with oxidants 62–63
 - pharmaceuticals degradation 63
 - textile wastewater treatment 63
 - modified biopolymers in 89–90
 - alginate-based adsorbents 93–94
 - cellulose-based adsorbents 90–92, 91
 - chitosan-based adsorbents 92–93, **93**
 - pesticide-contaminated water treatment 63–64
- wastewater treatment technologies 128
 - activated sludge process 130, 130
 - advanced oxidation technology 129–130, 130
 - constructed wetlands 128, 128
 - integrated fixed-film activated sludge 132, 133
 - membrane bioreactors 131, 132
 - membrane filtration technologies 129, 129
 - moving bed biofilm reactors 132, 132
 - rapid infiltration 128, 129
 - sequencing batch reactors 131, 131
- water 22, 29, 31, 53, 182; *see also specific terms*
 - color and odor 4
 - contamination 26–27, 87
 - demand 13, 33, 158
 - heavy metal sources in 114–115, 115
- waterborne diseases and contamination 162
- water contaminants
 - identification of 24
 - remote sensing technologies 26
 - water contamination 26–27
 - water quality testing 24–26
- water-contaminant treatment, *Moringa oleifera* seeds for drinking water 108–109
- dyes removal 107
- ion metals removal 106, **107**
- surfactant removal 107–108
- water crisis, issues and challenges in 33–42
- water cycle 159; *see also* hydrological cycle
 - global challenges 12, 12
 - climate change impacts 13–14
 - infrastructure 14
 - pollution and contamination 13
 - urbanization 14
 - water demand 13
 - water management and policy 14
 - water scarcity 13
- water quality influences 10
 - eutrophication 11
 - evaporation and pollutant concentration 11
 - feedback mechanisms 12
 - global implications 12
 - groundwater contamination 11–12
 - hydrological cycle 11
 - precipitation and acid rain 11
 - recharge 11–12
 - runoff 11

- Water-Energy-Food Nexus 174–175
- Water Framework Directive (WFD) 6, 15, 154, 173
- water infrastructure 14, 162, 163, 165
- water management
 - advancing 175
 - integrated water resources management 167–168, **168**
- water policies 14
 - in Morocco 28–29
- water pollution 13, 22, 31, 145
 - alarming levels of
 - heavy metals 13
 - microbial contaminants 13
 - nutrients 13
 - drinking water and sanitation in communities 150–151
 - effects on aquatic ecosystems 148
 - impact on environment
 - aquatic ecosystems 27
 - human health implications 27–28
 - types of 23
 - nonpoint sources 23–24
 - point source 23
- water quality 1–2, 3, 10, 16, 29–30, 158, 163, 166–167
 - analysis 24
 - biological parameters of 5
 - biological oxygen demand 5
 - eutrophication 6
 - microbial organisms 5
 - chemical parameters of 4, **5**
 - contaminants 5
 - dissolved oxygen 4
 - nutrients 4–5
 - pH level 4
 - global challenges 12, *12*
 - climate change impacts 13–14
 - infrastructure 14
 - pollution and contamination 13
 - urbanization 14
 - water demand 13
 - water management and policy 14
 - water scarcity 13
 - global water cycle processes and components 6, *6*
 - condensation and precipitation 7
 - evaporation and transpiration 7
 - global impact of 7–9, **8**
 - hydrological cycle 6–9, **8**
 - infiltration and percolation 7
 - runoff and collection 7
 - influences water cycle 10
 - eutrophication 11
 - evaporation and pollutant concentration 11
 - feedback mechanisms 12
 - global implications 12
 - groundwater contamination 11–12
 - hydrological cycle 11
 - precipitation and acid rain 11
 - recharge 11–12
 - runoff 11
 - and infrastructure 163
 - interconnection between global water cycle processes 9
 - concentration of pollutants 10
 - evaporation 10
 - groundwater quality 10
 - infiltration 10
 - pollutant transport 10
 - precipitation 9
 - surface runoff 10
 - Law 36-15 in service of 29
 - models 173
 - in Morocco 29–30
 - physical parameters of 3, **4**
 - color and odor 4
 - temperature 3
 - turbidity 3
 - solutions and strategic approaches 14–15
 - testing 24–26
- water quality indices (WQIs) 24, 25, 26, 27
- water reclamation and reuse 42, 184
- water resource management
 - hydrology
 - modeling 172–173
 - remote sensing 172
- water resources 158–159
 - and hydrology 158–159
- water reuse 188; *see also* wastewater reuse technologies
- water sample analysis 82, 82
- water-saving technologies 170, **171**
- water scarcity 13, 187
- watershed 15, 153, 154, 159, 172
- water supply 2, 40, 88, 158, 165, 174, 182
- water sustainability 182–184
 - advanced water treatment technologies 184–185
 - challenges and opportunities 186–187
 - definition and importance of 183
 - future directions 187–188
 - life cycle assessment 183–184
 - application 185–186
 - basic principles of 184
 - case studies 186
 - future directions 187–188
- water temperature 3, 11, 14, 160, 161
- water treatment 44
 - Moringa oleifera* plant for 100–101, *101*, 110
 - coagulation-active compounds identification 104
 - coagulation mechanism and functional groups of 104–106, *105*
 - seeds as coagulant 102–103, 109
 - seeds for water-contaminant treatment 106–109, **107**
 - reverse osmosis technology 79–82, *80–81*
 - cleaning of 85
 - trouble shooting **83–84**
 - technologies 14
- water turbidity 3
- wet combustion 39
- wet oxidation 39
- World Health Organization (WHO) 1, 4–5, 13, 148–150, 152, 153